Ten Questions on Indoor Greening and Environmental Quality

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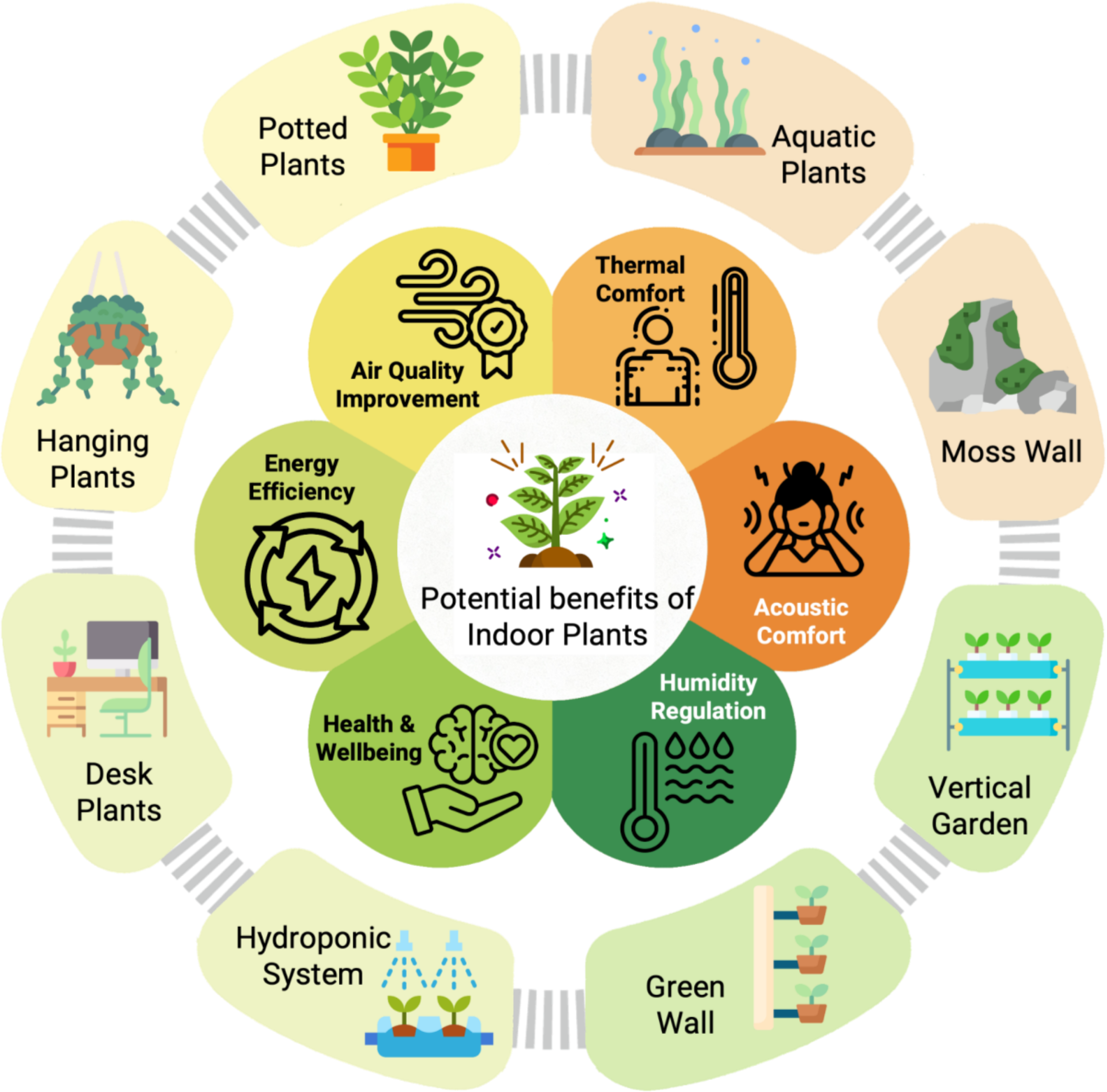
Graphical abstract



Abstract

While outdoor urban greening is recognised for its benefits, indoor green infrastructure (iGI) in shaping indoor environmental quality (IEQ) - including air quality, thermal comfort, and bioaerosols - remains underexplored. This ten-question paper identifies key challenges, opportunities, and research gaps in the iGI-IEQ nexus, organised under 10 questions across five thematic clusters: (1) biophysical and technical performance; (2) ecological and microbiological dynamics; (3) human health and wellbeing; (4) equity, access, and socio-economic factors; and (5) implementation and systems integration. Findings indicate that iGI can improve air quality, regulate humidity, and enhance thermal comfort. However, its performance depends strongly on plant density, species selection, and ventilation. Most evidence comes from controlled settings. iGI may offer positive psychological and cognitive benefits, and can reduce health inequalities through affordable indoor interventions. However, significant data scarcity exists for long-term field studies, indoor microbial ecosystem effects, and socio-economic accessibility. Widespread adoption of iGI requires quantification of proven benefit conditions, followed by overcoming technical, operational, and regulatory barriers via adaptive design, digital monitoring, and interdisciplinary collaboration. As a culminating synthesis, this study introduces a newly developed comprehensive matrix that classifies twenty-six indoor greening types across twenty IEQ parameters, incorporating an assessment of current data confidence. This matrix lays a foundational framework for informed decision-making and design guidance. This review offers evidence-based insights for researchers, policymakers, and practitioners to effectively leverage iGI where suitable, in creating healthier, climate-resilient residential and commercial buildings, addressing both immediate IEQ challenges and supporting long-term sustainability objectives.

Keywords: Indoor green infrastructure (iGI); Indoor greening; Sustainable Living; Climate resilience; Sustainable Development Goals; Indoor environmental quality

1. Introduction

Built, enclosed environments now constitute the predominant human habitat, with individuals spending up to 90% of their lives indoors [1,2]. The characteristics of these environments exert substantial influence on human health and wellbeing. Increasing evidence has established direct associations between modern artificial settings, contemporary lifestyles, and a broad spectrum of emerging psychological and physiological disorders [3]. These impacts are expected to intensify as a growing proportion of the global population transitions toward urbanised living patterns [4]. At the same time, climate change is reshaping the design of our indoor and outdoor environments, bringing higher temperatures, shifting humidity levels, and consequently altering pollution patterns in buildings. Efforts to improve energy efficiency in buildings aim to meet net-zero commitments adopted by many countries, such as the mid-century decarbonisation targets of the United Kingdom and the European Union, and a growing number of international governments [5,6]. There is a risk of compromising indoor environmental quality (IEQ), particularly when enhanced energy efficiency leads to reduced ventilation without properly addressing indoor pollution sources. While outdoor greening solutions such as green walls and trees are well-researched [7–9], the evidence surrounding the role of indoor green infrastructure (iGI), also referred to as indoor greening, in influencing IEQ remains limited and fragmented.

The incorporation of various iGI - including potted plants, indoor green walls and screens, and moss panels, grown either in conventional media or hydroponically - interacts directly with the built environment and occupants, thereby influencing IEQ [10]. IEQ is a multifaceted concept encompassing indoor air quality (IAQ), thermal comfort, bioaerosols (bacteria, viruses, fungi, pollen, mould and allergens), lighting, and acoustics, all of which can affect human health and well-being [11,12]. As illustrated in Figure 1, iGI can be grouped into passive, transitional, and active types based on their level of technological integration, encompassing 21 commonly used indoor greening systems. However, only a limited number of studies have explored how indoor greening influences these multidimensional aspects [10].

Most existing work has focused on the removal of specific pollutants or humidity regulation, providing the foundations to now explore the broader pathways and opportunities. Research is particularly scarce on the effects of plants on indoor air dynamics; on plant-microbiome interactions *(*e.g., phyllosphere and rhizosphere communities) and their potential interactions with human and surface microbiomes; and on the emission and fate of biogenic volatile organic compounds (BVOCs) released indoors [13]. Equally, the contribution of vegetation to secondary IEQ parameters such as acoustic performance has received little systematic attention. Notably, existing studies rely on chamber-based or closed-environment setups, which do not reflect real-world conditions or account for variations in plant placement, ventilation patterns, and occupant behaviours, thus limiting their generalisability to occupied buildings [14]. Furthermore, standardised metrics for evaluating the impact of iGI on IEQ parameters are lacking, limiting cross-study comparability. Long-term, large-scale investigations that integrate field-based measurements with modelling are essential, covering both residential and commercial settings. Therefore, while indoor greening holds promise, robust multidisciplinary evidence is required to clarify its potential for improving IEQ and ensuring that iGI does not exacerbate existing health and wellbeing inequalities.

Climate change affects IEQ through complex interactions between building energy efficiency, shifting outdoor pollution patterns, and adaptive occupant behaviour. Energy efficiency measures often reduce ventilation, while climate-sensitive pollutants (e.g. ozone and bVOCs) increasingly infiltrate buildings during warm periods. Simultaneously, climate-driven humidity can increase elevated mould risk. These combined challenges highlight the need for frameworks linking IEQ with climate resilience. Meanwhile, outdoor urban greening initiatives are advancing rapidly worldwide, with London's target of 1.5 million m^2 of green roofs serving as one illustrative example [15]. Despite growing interest in green design, the contribution of iGI to improving IEQ has received limited scientific attention.

Table 1 summarises recent publications on indoor greening and related reviews, which differ widely in focus, ranging from broad conceptual discussions to highly specific analyses of particular environmental parameters or pollutants. For example, some address urban greenery and resilient cities [16] or the reliability of subjective IEQ rating scales [17], while others focus on specific pollutants such as ultrafine particles [19] or examine IAQ within green building certification systems [26]. Additionally, several related reviews examine the role of indoor plants and greening systems to IEQ, covering topics like indoor phytoremediation and pollutant removal [33,37,39], links between indoor plants to health and wellbeing [31,34], and broader evaluations of green systems such as vertical greening walls and biofilters in relation to air quality, thermal comfort, and psychological benefits [10,32,36]. Together, these studies highlight key IEQ dimensions, including health risks, energy efficiency, and social justice, from diverse yet specialised perspectives. This paper is distinctive in applying the ten-question framework specifically to iGI, synthesising evidence across technical, microbiological, health, socio-economic, and place dimensions, providing more powerful interdisciplinary approaches to address knowledge gaps on iGI, IEQ and climate resilience.

The ten research questions presented in this paper are broadly categorised into five core thematic clusters (TC), with some questions associated with more than one cluster. As illustrated in Figure 2 (and described in detail in Table S1), these clusters form a cohesive framework for understanding iGI, and include:

- TC1-Biophysical and technical performance (assessing impact on IEQ parameters, HVAC integration, energy efficiency, seasonal performance; Q1, Q2, Q3, Q4, Q5, Q9).
- TC2-Ecological and microbiological dynamics (rewilding microbial communities, managing mould/bioaerosol risks; Q5, Q6).

- TC3-Human health and wellbeing (effects on cognition, emotion, physiology, mental health, thermal sensation, and behavioural change; Q4, Q6, Q7).
- TC4-Equity, access, and socio-economic impact (benefits across social vulnerability factors; Q8).
- TC5-Implementation and systems integration (existing interventions, engineering barriers, real-world effectiveness; Q3, Q9, Q10).

Together, these themes represent a logical progression from investigating the fundamental technical performance of iGI to understanding its broader human, and systemic impact. Lastly, the paper offers suggestions for future research to accelerate iGI adoption and better understand the challenges of real-world implementation.

2. Ten questions and their answers on the IEQ and iGI

TC1, 'biophysical and technical performance' (Q1-Q5), addresses the overarching question: How do plants and the building environment interact to affect each other? The understanding of these fundamental mechanisms of iGI will provide the essential conceptual grounding for how different systems function (degree of technological integration and ecological-mechanical interaction), reflecting the types of interventions and technical feasibility discussed in Q9.

2.1 Q1. How does iGI impact IEQ?

Vegetation, indoor and outdoor, can influence the temperature and relative humidity through evapotranspiration, as well as take up carbon dioxide (CO_2), absorb, adsorb or metabolise a wide range of other gaseous compounds, including ozone (O_3), nitrogen oxides (NO_x), sulphur dioxide (SO_2), and volatile organic compounds (VOCs) [10, 44, 45, 46]. However, empirical studies indicate that at the room scale, these effects are typically modest, with reported changes in air temperature generally ≤0.5–1.0 °C and relative humidity ≤2–5% under typical indoor plant densities and ventilation rates, often below perceptual comfort thresholds, while CO_2 removal by plants is negligible compared with occupant emissions and ventilation-driven air exchange [46]. These processes are not static, as diurnal variations in plant metabolism influence IEQ through daytime photosynthetic CO_2 uptake and nighttime respiratory release accompanied by altered transpiration rates, effects that are generally negligible in unoccupied offices but relevant for night-time occupied spaces such as bedrooms. Species such as *Dracaena fragrans*, *Spathiphyllum wallisii*, and *Zamioculcas zamiifolia* have been shown to contribute to the reduction of indoor air pollutants under controlled conditions [44]. Early work carried out by NASA in the late 1980s showed that a rudimentary air cleaning system combining activated carbon with different low-light-requiring indoor houseplants inside a sealed 0.44 m^3 experimental chamber was able to remove VOCs, including benzene, formaldehyde and trichloroethylene, from the chamber air [45]. Furthermore, studies have shown that indoor plants reduce NO_2 concentrations based on chamber experiments, with *D. fragrans* showing the highest removal efficiency under illuminated and moist conditions, indicating their additional potential to mitigate gaseous pollutants indoors [44]. Beyond air quality, plants may help regulate indoor climate by affecting temperature and humidity [10,46,47], supporting relative humidity levels in the recommended 40–60 % range that promotes health and limits mould-growth [48,49].

However, the experimental conditions used for these studies are often unrepresentative of real indoor environments. In fact, it has been estimated that 10-1000 plants per m^2 of floor area would be needed to compete with the removal of VOCs via typical building ventilation rates [50]. Selecting plants for specific temperature and humidity conditions can also optimise VOC removal, given that different plants become more or less effective at VOC removal as temperature and humidity change [51]. Furthermore, many plants emit VOCs, from leaf surfaces and from flowers contributing to their distinctive floral scents, which are thought to be signals within the plant, or to other plants, animals and microbes [52]. The introduction of plant species selected for indoors can, therefore, have quite a nuanced effect on the subsequent IAQ, depending on the plant species and density.

However, the role of iGI in impacting the IEQ at multiple, interrelated levels are context dependent and sensitive to plant density, species, room volume, ventilation rates, and background indoor conditions, as plant-driven processes such as evapotranspiration and gas exchange operate at the scale of leaf surfaces and immediate surroundings, whereas perceived IEQ reflects room-scale air mixing, heat transfer, and ventilation dynamics. Consequently, localised cooling or humidification effects may be measurable near planted surfaces but become increasingly diluted at whole-room scale, particularly in mechanically ventilated or thermally conditioned spaces [46].. Through the evapotranspiration process, plants have the potential to improve the relative humidity of the rooms and enhance the thermal comfort, establishing a more stable microclimate which indirectly mitigates the effects of outdoor environment fluctuations on IEQ, provided the iGI system is scaled appropriately to the room volume, for example, an 8 m^2 active living wall installed in a 340 m^3 hall was shown to reduce nearby air temperature by 0.8-4.8 °C under typical indoor condition[46]. Thereby, iGI, such as green walls, potted plants, and botanical filtration units, can impact the IEQ through multiple mechanisms: (1) Plant-induced increase in RH stabilises the indoor microclimate and reduces the thermal gradient between indoors and outdoors, thereby dampening the buoyancy-driven component of natural ventilation and infiltration. A lower indoor–outdoor humidity difference weakens the stack effect and lessens the influx of outdoor air carrying PM and other pollutants (Kaur et al., 2025). (2) Elevated humidity increases the hygroscopic growth of particles, thereby enhancing the gravitational settling and deposition of PM [53]. In addition, water vapour from the leavese along with the complex micro-texture of the leaf surface, providing a substratum for impaction and interception of PM, enhancing the dry deposition and absorption of PM. Also, the plant canopy dampens the local air turbulence, reducing the resuspension of dust particles [54–56].

(3) Acting as botanical biofilters as active biofilters draw indoor air through the soil substrate, trapping particles by impaction and filtering the air [57]. (4) Alongside, the phyllospheric and rhizospheric microbes also contribute to degrading various types of pollutants [58]. (5) Indoor plant systems, whether active or passive, can affect indoor microbial communities by serving as living sources and mediators of microbial exchange within built environments (Dockx et al., 2021). (6) Vegetation has also been proposed as a passive means of improving indoor acoustic comfort. Plants and their growth media can attenuate sound through a combination of reflection, scattering, absorption, and interference of sound waves, thereby reducing overall noise levels within interior spaces [59,60]. Table S2 summarises empirical studies that have investigated these multifaceted impacts of indoor plants on key parameters of IEQ, including air quality, humidity, temperature regulation, particulate deposition, and acoustic comfort, highlighting the diversity of plant species, experimental setups, and observed outcomes. These interconnected strategies collectively enhance the quality of indoor spaces, helping to reinforce overall IEQ (Figure 3).

Key take-home messages: (i) Indoor greening (iGI) influences IEQ through air quality, thermal–humidity balance, particulate matter reduction, and acoustic comfort; (ii) Plants improve IEQ via pollutant absorption and deposition, evapotranspiration, microbial biofiltration, and sound attenuation; (iii) Effects vary by plant species, density, and environmental conditions, and spatial scale.

Research gaps: (i) Determining optimal plant density, species selection, and environmental conditions needed to enhance IEQ through humidity moderation, temperature regulation, energy reduction, and pollutant removal. (ii) Characterising interactions between plant-induced humidity and indoor-outdoor air exchange. (iii) Developing mechanistic and predictive models to assess if and how specific iGI configurations can reliably improve indoor environmental conditions.

2.2 Q2. What is the impact of indoor environmental conditions on a plant's ability to deliver IEQ improvements?

Delivery of many of the documented benefits of indoor greening, primarily the regulation of ambient humidity and removal of gaseous pollutants such as CO_2, depends on plants remaining physiologically active (e.g., taking up pollutants via open stomata) and growing, as biomass and leaf area determine pollutant uptake rates and people's perceptions of plants' impact on human wellbeing [61,62]. The key limiting factor for indoor plant function is light intensity [44,63,64]. Plants used in indoor environments are typically species adapted to low-light tropical understorey habitats [65]. However, for many species, typical indoor light levels (~10 μmol m^{-2} s^{-1}) of Photosynthetic Photon Flux Density within the visible spectrum of 400-700 nm [66,67] are lower than the light compensation point (LCP), the threshold at which photosynthetic CO_2 uptake exceeds respiratory release. For example, *Epipremnum aureum* and *Ficus repens* exhibit LCPs > 40 μmol m^{-2} s^{-1} [66]. Therefore, careful species selection, optimal positioning relative to light sources (e.g. near windows), and careful selection of supplementary lighting [68] are essential for plants to thrive. Even with additional light, plants' physiological activity indoors in most cases remains lower than outdoors, and substantial plant numbers are required to achieve room-scale pollutant reduction, where effects are often minimal [69]; see Section 2.1). Systems such as living pictures, green screens, and walls can increase plant numbers and CO_2 removal without occupying extended floor space [70,71]. In addition, incorporating active airflow enhances the removal of VOCs [72]. Although other factors, such as substrate moisture, humidity, and air movement, affect stomatal activity, light remains the dominant limiting factor for plant function indoors [73]. Plants' interaction with light is complex, and additionally, consideration is required to provide light intensity and spectra to meet both occupants' and plants' needs [68].

Water availability has a strong influence on plant productivity in outdoor systems, but indoor plant water use is lower, primarily due to reduced light levels (Table 2). This must be considered when managing potted plants and green installations, as anecdotal evidence suggests that overwatering is a leading cause of plant decline. In active green wall systems, substrate moisture and irrigation rate influence airflow through the substrate, microbial composition [74], and, consequently, the wall's air-remediation capacity, with lower irrigation rates generally being more beneficial [74]. Substrate moisture also contributes to the removal of gaseous pollutants, such as NO_2, which dissolves readily in water. However, soil moisture only becomes limiting for NO_2 uptake under extremely dry conditions (<10%), meaning that most substrates contain sufficient water for removal [44]. For CO_2, hydroculture systems achieve markedly higher removal rates than conventional potting media [75]. Substrate water content also indirectly affects ambient humidity: chamber experiments show optimally watered plants elevate humidity [62], but room-scale results are inconsistent, sometimes increasing humidity [69] and sometimes not [62]. Excess humidity, coupled with low temperature and a reduced vapour-pressure deficit, can in turn lower stomatal conductance and limit plant contributions to IEQ [62].

Even when plants are physiologically active and environmental factors are optimised, their ability to improve IEQ remains strongly dependent on air exchange or ventilation rates (Section 2.3). These rates vary widely and are often poorly characterised, particularly in naturally ventilated buildings such as typical UK homes. Typical air exchange rates (AER) in UK homes are approximately 1 h^{-1}, as reported in the foundational indoor air literature [76] and supported by CO_2-decay measurements from over 300 dwellings. Variability is influenced by external wind speeds, building fabric (e.g., leaky Victorian vs. airtight modern homes), and occupant behaviour (e.g., frequency of window opening or extractor use). For instance, effective kitchen extraction can maintain NO_2 below the WHO 1-h guideline of 200 $\mu g/m^3$, a standard established for outdoor air but commonly used as a reference for indoor cooking emissions [77]. High air exchange with clean outdoor air can therefore outweigh any plant-mediated improvements and, where feasible, remains the most effective means of enhancing IEQ. However, the balance between ventilation and energy efficiency must be carefully assessed [78], supporting the consideration of indoor greening as a complementary strategy for maintaining healthy indoor air.

Key take-home messages: (i) Indoor greening effectiveness predominantly depends on plant physiological activity, particularly stomatal function and growth; (ii) light availability primarily limits indoor plant health, with water balance, air movements and nutrients as secondary factors; (iii) overwatering and inadequate lighting cause plant decline, reducing pollutant-removal and humidity-regulation benefits; (iv) ventilation rates strongly impact observed IEQ effects, with high air exchange often negating plant-mediated improvements.

Research gaps**:** (i) optimising light intensity, humidity, substrate moisture, nutrients, and airflow to sustain plant physiological activity; (ii) conducting long-term measurements in actual buildings to quantify plant-mediated IEQ improvements; (iii) evaluating how species selection, planting density, system design and real-world maintenance practices affect pollutant removal and humidity regulation, and (iv) assessing the net energy implications of indoor greening systems, including the electricity demand of supplementary plant lighting relative to any indirect, system-level energy effects.

2.3 Q3. How does iGI integrated with building heating, ventilation and air conditioning (HVAC) systems affect IEQ?

HVAC systems are typically designed to maintain optimum indoor environmental conditions, prioritising thermal comfort, with some configured to optimise IEQ by also reducing CO_2 levels and filtering PM entrained in the air. A typical consequence of these control systems is increased building energy use [79]. At present, iGI is a solution that could positively impact a HVAC system's energy efficiency by: (1) reducing thermal loads via air cooling through evapotranspiration; (2) enabling phytoremediation of indoor air to absorb CO_2, thus lowering fresh air demand; and (3) using biofiltration to remove PM and VOCs from the indoor air in order to reduce filter loading in the ventilation system [10, 80] (Figure 4). While these potential benefits are encouraging research on their integration with the design and operation of HVAC systems is lacking. Both are critical to optimise benefits and trade-offs. Some evidence on the scale of these impacts and nature of the trades-offs include the following.

Engineered greening systems integrated with HVAC systems provide stronger and more beneficial impacts than standalone configurations. For example, integrating an active botanical filter with a saturated growing substrate and a 680 cm^2 surface area into a HVAC system's air distribution network enhanced the cooling performance of the supply air at the distribution vent under dynamic conditions, achieving temperature reductions up to 4.2 °C, and a 34.9% increase in RH with mass air flow rates ranging from 0.016-0.026 kg/s [81]. An indoor 1 m^2 green wall situated in a 15.6 m^2 room is capable of balancing 16% of respiratory CO_2 and estimated to supply 1.67% of the ventilation requirements for a single occupant [70]. An active green wall (AGW) integrated with a HVAC system lowered winter and transition-season temperatures by 1.0-1.4 °C, raised RH by 11-21%, while reducing CO_2 in a 25 m^2 room [82]. Likewise, a 15 m^2 living wall cooled a local 140 m^3 office air by 2.5-4.5 °C, reduced CO_2 concentrations by up to 50%, and delivered 20% energy savings (~1400 kWh/year) through lower ventilation requirements [83]. Extending these findings, EnergyPlus simulations demonstrated that iGI can cut fresh air demand in a 30 m^2 office by 14-39% and reduce energy consumption by 11-28%, with savings greatest in colder, humid climates [84]. A further dimension comes from hydroponic farming, where a 100-plant system consisting of two 1.43 m wide frames designed with ten stacked growing layers containing ten heads of pakchoi in a 30 m^2 office also reduced

CO_2 concentrations by 26-34% and decreased energy usage by 13-58%, depending on occupancy rates and growth stage [85].

Azolla biofilters were found to reduce indoor PM and CO_2 concentrations by 40 and 50% respectively within short exposure times and have the potential for integration into existing HVAC designs [86]. A case study of a Chinese classroom with a 120 m^3 room volume found a 9 m^2 AGW with 2.36 ACH removed 42.6 % more PM than a HVAC system supplying 2.5 ACH with a MERV 13 filter [87]. In most real-world scenarios with full room scale iGI implementation, as addressed in Q1, the iGI volume required to replace the fresh air supply and filtration system is unrealistically large, but scope exists to improve HVAC system performance through iGI integration. For VOC concentrations, a reduction can occur using iGI, but a decrease in the removal capacity is observed at higher ACHs [88]. Furthermore, the associated RH increase was also found to have no impact on the presence of mould spores in the summer (winter conditions were not tested), a common assumption with iGIs [89]. There is also no indication that the use of active airflow through green walls acting as biofilters leads to increased bioaerosol concentrations indoors, or breaches WHO guidelines [90]. The key findings with context, iGI tested and climate regions, including seasonal settings can all be found in Table S3.

Key take-home messages: Emerging evidence suggests integrating iGI with HVAC systems enhances energy efficiency and IEQ by reducing thermal loads, decreasing CO_2 levels, lowering fresh air demand and filtering pollutants [36,91]. Engineered greening systems improve IEQ with air flows over leaves and through substrate. However, evidence gaps remain regarding full integration and maximising iGI impact.

Research gaps: (i) Energy consumption of active engineered iGI ventilation fans and their IEQ performance; (ii) how iGi-improved IEQ affects HVAC filtration efficiency and fan energy use through reduced filter loading; (iii) Relationships between climate zones, seasons, HVAC operations and iGI selection on mould growth and bioaerosols [92]; (iv) Optimal iGI placement by location to minimise energy use and reduce pollutants. Future research should focus holistically on iGI-HVAC integration, addressing ventilation flows, humidity distribution, and systematic optimisation of placement, type and area to understand these trade-offs.

2.4 Q4. How does iGI affect thermal sensation and comfort?

Indoor greening is increasingly examined as a way to influence thermal sensation and perceived comfort, even where objective indoor conditions remain unchanged. In this question, "comfort" refers specifically to thermal comfort outcomes, including thermal sensation votes, thermal acceptability/satisfaction, perceived heat stress, and thermo-physiological responses such as skin temperature. Across experimental, field, and simulation studies, evidence shows that plants, whether potted, in green walls, or as integrated systems, consistently shift subjective appraisals of the thermal environment in favourable ways. These effects arise from modest microclimatic regulation (evapotranspiration, humidity moderation) and stronger visual and psychological pathways linked to biophilia (Figure 5). Broader psychological wellbeing outcomes (e.g., mood, stress restoration, cognition/productivity, social connectedness) are synthesised separately in Q7 to maintain a clear separation between thermal comfort as an IEQ performance endpoint and wider wellbeing or behavioural outcomes.

Controlled experiments provide some of the clearest evidence. In an Indian open-plan classroom, participants exposed to eight potted plants reported cooler thermal sensation (TSV; a self-reported index of perceived warmth or coolness on the ASHRAE 7-point scale ranging from −3 = cold to +3 = hot) by 0.42 scale points which can be interpreted as roughly the perceptual equivalent of ~1 °C in operative temperature while thermal satisfaction remained stable over the session; by contrast, the no-plant group's satisfaction declined and their thermal sensation drifted warmer. These differences occurred despite comparable measured indoor conditions (i.e., air temperature and relative humidity were maintained within similar bounds across plants and no-plant sessions) [93]. In a laboratory study manipulating indoor green wall "dose" using Green View Index (GVI), Ma et al. found that thermal comfort increased with greater visual greenery (GVI 0%, 5%, 15%), with mean thermal comfort vote changes of +0.02, +0.25, and +0.44 relative to pre-trial conditions; however, because only three discrete doses were tested, the form of the relationship (linear vs saturation) beyond 15% GVI remains unknown [94]. A hydroponic living wall lowered occupant thermal sensation by up to 0.70 TSV (thermal sensation vote) at 24.5 °C (interpreted as 2.2 °C perceived cooling), increased comfort votes, flattened the TSV-temperature slopes, and narrowed gender-related comfort differences [95].

Taken together, these occupant responses indicate that indoor greening can widen the range of temperatures judged acceptable and comfortable, enabling people to tolerate warmer cooling setpoints; corresponding HVAC implications have therefore been modelled suggesting 7-9% energy savings when setpoints are raised within the expanded acceptability range [95]. Similarly, immersive virtual reality (VR) showed that, at SET* 30 °C under identical measured chamber conditions, viewing a biophilic office reduced perceived heat stress by 1.6 °C (psychological cooling), underscoring the importance of visual cues [96]. Overall, these findings imply that indoor greening can sustain comfort at higher setpoints, with the potential for meaningful reductions in cooling energy use. A comparative summary of these and related studies, including interventions, methods, and comfort outcomes, is provided in Table 3.

Field and seasonal studies extend these findings to real workplaces, consistently showing benefits in perceived comfort and acceptability. In a four-season quasi-experiment in the Netherlands, office workers exposed to substantial indoor planting were nearly twice as likely to report being thermally comfortable, an effect observed across seasons (including winter) and under adjusted setpoints [97]. In Warsaw offices, thermal sensation votes largely remained neutral, yet thermal acceptability rose to 96% following the installation of green walls, alongside improved perceptions of humidity and air freshness [98]. Similarly, a multi-site Dutch field study found that indoor plants significantly reduced complaints about dry air**,** while a binary indicator of being “too hot and/or too cold” was unchanged, indicating that office greening mainly improves perceived acceptability and dryness-related comfort rather than shifting temperature sensation per see [104]. These occupant-reported outcomes are supported by measured field evidence showing that indoor plants can modestly increase indoor humidity particularly under dry seasonals, while measured air temperature is minimally affected [62,69].

Laboratory studies integrating greening with HVAC systems report occupant-centred improvements with higher perceived thermal comfort, thermal sensation shifting toward neutral, and physiological responses moving closer to thermal neutrality, supported by measured microclimatic changes. In Liu & Meng [99], participants in the living wall-ventilation room reported and higher thermal comfort (+0.53 scale points), with thermal sensation shifting from slightly warm toward near-neutral and mean skin temperatures closer to thermal neutrality [99]; measured indoor air temperature decreased by 1.45 °C and relative humidity increased by 19.1% compared with a sealed control room. In winter, humidity rose by 10.8%, thermal sensation shifted toward neutral, and comfort improved by +1.1 scale points when a 2 m^2 living wall was paired with a split air conditioner in a 25 m^3 room/office [100]. Liu et al. (2025) extended this to annual testing: an active plant wall stabilised temperature and humidity across seasons, maintained mean skin temperature near the neutral 33.2 °C, and sustained “slightly comfortable” votes across seasons [82].

Simulation studies extend these experimental patterns by quantifying the coupled sensible–latent impacts of indoor greening at building scale. An EnergyPlus module was developed to capture evapotranspiration, convection, and radiation from living walls, predicting sensible cooling reductions of 9-14% at 30% leaf-to-floor ratios, while supporting comfortable indoor conditions [101]. However, the same evapotranspiration increases latent loads, meaning humidity control becomes a prerequisite for net energy benefit. This trade-off aligns with broader evidence that indoor greening improves comfort through biophysical mechanisms (evapotranspiration) and psychological pathways, though care is needed to avoid over-humidification [47].

Evidence at residential scales supports both the physical and perceptual comfort pathways. In a tropical apartment, balcony potted plants lowered adjacent indoor air temperature by up to 2.3 °C under comparable solar conditions, directly lowering heat stress and improving thermal comfort via combined shading, evapotranspiration, and surface buffering [102], though accompanied by higher RH that can offset comfort if unmanaged. Complementing these physical effects, immersive VR results suggest biophilic interiors accelerate stress recovery, indicating an added psychological contribution to comfort beyond microclimate alone [103], with these broader restorative mechanisms discussed in detail in Q7.

Key take-home messages: (i) indoor greening can enhance thermal comfort even when measured temperature changes are small; (ii) comfort benefits occur primarily through perceptual and psychological mechanisms, with modest humidity regulation and limited evaporative cooling; (iii) Positive effects are reported across climates, seasons, and building types, but show clear scale and visibility dependence, limiting direct extrapolation from small demonstrators; (iv) primary systems implication is that iGI can widen thermal acceptability ranges, enabling adaptive temperature setpoints strategies where humidity is appropriately managed.

Research gaps remain on: (i) longer-term trials with diverse populations beyond student samples, accounting for novelty and expectation effects; (ii) integration of physiological measures (skin temperature, HRV) with subjective responses, and local microclimate (including MRT/air movement); (iii) large-scale field trials linking iGI–HVAC operation to perceived thermal comfort; (iv) systematic comparisons of plant species, densities, layouts and visual "dose" to identify scaling or saturation effects; and (v) trade-offs, including over-humidification, allergen/bioaerosol exposure, and performance decay over time. Addressing these will advance indoor greening from demonstrations to evidence-based comfort and energy strategies.

TC2, "ecological and microbiological dynamics" (Q5, Q6), addresses the overarching question: how does indoor greening interact with indoor microbial communities, and what are the implications for microbial rewilding, air hygiene, and the management of mould and bioaerosol risks?

2.5 Q5. How can advanced technologies integrated with iGI predict and maintain IEQ while reducing dampness and health risks of exposure to bioaerosols?

Recent technological progress has allowed iGI to evolve from a passive design feature into an active, cyber-physical system capable of predicting and managing IEQ. Building upon the physiological and perceptual mechanisms outlined in earlier sections, this question examines how data-driven advanced technologies can anticipate and control fluctuations in humidity and bioaerosol load, thereby reducing dampness-related risks and safeguarding occupant health in indoor environments. To map this advanced technological landscape, Table S4 summarises three overarching layers: (i) Smart Sensing & IoT-Based Monitoring, (ii) AI &

Digital-Twin Analytics, and (iii) Intelligent & Hybrid Environmental Control Systems, together with representative studies. Figure 6 illustrates the conceptual integrated feedback framework of intelligent iGI systems, where IoT-based sensing, AI analytics, and adaptive control interact to maintain optimal IEQ by minimising bioaerosols and dampness, also highlighting key challenges that constrain large-scale implementation of self-regulating iGI technologies.

Advances in the Internet of Things (IoT) have enabled continuous, high-resolution observation of iGI-indoor interactions. Distributed, low-cost networks now measure CO_2, VOCs, ozone, particulate matter, temperature, and humidity, alongside plant indicators such as leaf-surface temperature and substrate moisture [105–107]. These variables are vital for identifying microbial infestation thresholds: the WHO and multiple studies confirm RH > 60 % is consistently linked to mould growth and dampness symptoms [108,109]. IoT-instrumented living-wall experiments in two climate-controlled rooms (each 20-25 m^2 floor area; wall modules ≈ 2.5 m × 2 m) showed 10-15 % RH increases linked to evapotranspiration and CO_2 uptake gradients of 50-150 ppm, trackable in real time [110]. Modern IoT frameworks with fog gateways, which locally process data before cloud transmission, support predictive modelling and early-warning dashboards while reducing latency and bandwidth demand. Optical and DNA-based bioaerosol sensors are emerging to detect microbial activity near biofilters, adding a hygienic dimension to IEQ metrics [111].

Translating monitoring into predictive management can be addressed using physics-based and empirical engineering models derived from first-principles formulations. Data-driven methods, including artificial intelligence and machine learning, may be used as complementary tools to represent nonlinear interactions among plant physiology, occupancy, and ventilation dynamics where system complexity or data volume limits purely mechanistic approaches. ML models trained on multi-sensor datasets achieve >85% accuracy in predicting mould-growth potential from humidity and temperature inputs [112]. In iGI contexts, such analytics distinguish beneficial humidity moderation (a 10–15% RH increase that improves freshness) from excessive moisture (> 60% RH) that raises microbial risk [62]. Broader AI applications forecast CO_2 (mean error < 50 ppm), VOC evolution, and adaptive ventilation strategies [113]. Coupled with iGI sensor data, soil moisture, photosynthetically active radiation, or leaf temperature, these models infer evapotranspiration rates and locate potential condensation zones, enabling proactive IEQ control. AI-driven frameworks enhance prediction but often rely on correlations rather than causation, posing equity risks if underlying data are biased [114]. Incorporating causal reasoning and transparent methodologies is crucial to avoid perpetuating existing disparities. In practice, this involves developing expert-informed, mechanistic causal models at the outset to define plausible cause–effect relationships, which can then guide and constrain AI-based analyses in an interpretable and physically meaningful way.

Digital-twin (DT) technology extends this predictive capability by constructing dynamic virtual replicas of iGI-building systems continuously updated with sensor data [115]. Experimental and office-scale studies have demonstrated that indoor vegetation integrated within typical room-scale environments contributes to CO_2 uptake, VOC removal, and indoor humidity regulation [41,64,116]. These parameters feed DTs to simulate pollutant fluxes, moisture dynamics, and microbial risk under variable occupancy and weather. Scenario testing, such as winter low-light limitation or summer RH > 70% extremes, supports countermeasures including supplemental lighting or targeted dehumidification [117], reducing dampness and bioaerosol risk. DT prototypes for hydroponic and aquaponic walls confirm the feasibility of linking biological performance with predictive microbial risk [118,119].

The third layer embodies smart automated control, translating predictive insights into self-regulating environmental responses. Integrating sensor feedback and AI predictions with HVAC, variable-air-volume diffusers, adaptive irrigation, and dehumidification units, these systems autonomously maintain optimal IEQ [120,121]. When humidity spikes, the system triggers zonal dehumidification or adjusts irrigation rates, achieving up to 40 % faster recovery than manual operation. Active green walls with embedded fans and moisture-feedback irrigation keep RH within ±3 % of target, preserving plant health and preventing condensation. In recent real-building applications, IoT-linked modules self-activate when bioaerosol or VOC levels rise, integrating with energy-recovery ventilation to maintain thermal and latent-load balance and reduce HVAC energy demand by 15–25% [122].

Key take-home messages: (i) advanced technologies transform iGI into a responsive ecological interface between plants, occupants, and indoor environments. Smart sensors and IoT networks detect environmental and microbial changes, while AI and digital twins predict issues and optimise responses; (ii) automated control systems integrate with HVAC, irrigation, and filtration to maintain stable conditions that improve health, comfort, energy performance and reduce microbial risk; (iii) future research should emphasise long-term field validation, data standardisation, and air hygiene monitoring.

Research gaps: (i) sensor drift and reliability issues reduce data precision, with RH offsets masking subtle iGI effects and VOC sensors lacking long-term accuracy; (ii) AI models fail across different climates or building types without retraining; (iii) high cost and low awareness limit advanced sensing and automation adoption in typical homes; (iv) poor data interoperability between IoT platforms restricts building-management system integration; (v) absence of policies and standards for IEQ monitoring and microbial-risk control slows large-scale implementation.

2.6 Q6. Can iGI contribute to rewilding the indoor microbial ecosystems and thereby promote human health?

Indoor environments have become the dominant human habitat [1], yet their ecological dynamics remain poorly understood. Existing evidence indicates that microbial diversity indoors is markedly reduced compared to natural outdoor environments [28,123] and that such diminished exposure to diverse and complex microbial communities has been associated with a higher prevalence of acute and chronic health conditions worldwide, including obesity, asthma, autoimmune disorders, juvenile (type 1) diabetes and autism [124–126]. These relationships are largely correlational and causal links remain unestablished. While the underlying mechanisms remain incompletely understood, this section adopts a critical, hypothesis-driven perspective to examine whether indoor plants may contribute to changes in the composition and diversity of microbial communities in built environments [13,28,127,128] (Figure 7). In turn, whether these have health benefits needs to be investigated.

Indoor environments host a dynamic microbial world [129] of bacteria, fungi, viruses, and other microorganisms [130]. Some enter passively, while others actively adapt to indoor niches with unique chemical and physical conditions [129]. Research on indoor microbial habitats is still very new [131], and there is no clear definition of a "healthy" indoor microbiome due to its complexity and many influencing factors [132]. We do know that a "core" indoor microbiome has been identified across most spaces [133,134], with its composition largely associated with human occupant density and activity [135,136]. Animals (pets and pests) contribute through skin, hair, faeces, and saliva [129,137], and taxa such as dust mites and cockroaches are well established sources of indoor allergens [138]. Environmental microbes also enter via vectors including people, pets, air systems, and plumbing [139–141]. Cultural and environmental factors, lifestyle, hygiene norms, selective breeding, building form, materials, and technology, have all been associated with variations in microbial diversity and persistence indoors [123,134,135].

Plants harbor a diverse community of symbiotic microorganisms [142], many of which are regarded as neutral or potentially beneficial to human health [143]: (1) Indoor plant surfaces, largely unaffected by chemical cleaning, may support localized microbial ecosystems [144]; (2) Indoor plants have been proposed to act as reservoirs of microbial diversity, stabilizing ecosystems through their resilience to biotic and abiotic stressors. Dockx et al. (2022) found that interiors with more plants had fewer human-associated bacteria and a greater share of environmentally derived taxa, indicating an association between indoor vegetation and altered microbial community composition [127]. This diversification has been hypothesised as a key strategy for mitigating pathogens by increasing competition for the same resources [13,128]; (3) Plants actively exchange microbes with symbionts and their environment [145], including interactions with indoor biological contaminants such as pollen. Soil-rhizosphere and air-phyllosphere interactions exemplify the dynamic exchange of microorganisms within plant-associated environments [144,146], while pollen and seeds act as vectors of microbial dispersal [147,148]. Consequently, closely related taxa are found across distinct microbiomes, including soil, plant surfaces, and even human skin [149,150]. Indoor vegetation has also been proposed as a botanical biofilter, with experimental studies suggesting that air drawn through the soil substrate can facilitate processing by rhizosphere and phyllosphere microbes [57,58].

While these opportunities highlight significant potential, they also expose knowledge gaps that warrant further empirical investigation [128]. Few studies have addressed the potential contribution of iGIs to diversify the indoor microbiome (Table S5). Evidence suggests an influence on microbial communities, while causality and health relevance remain uncertain. Future research should deepen our understanding of how biodiversity interventions shape airborne and phyllosphere microbiomes, and how targeted microbial taxa (such as anti-inflammatory health-associated bacteria) may influence human microbial communities [151]. Particular attention is needed to clarify the ability of plant-associated microbial communities to maintain their diversity under prolonged indoor conditions, together with the dynamics of species-specific microbiomes, including their overlap, interactions with other indoor microbial assemblages, and potential influence on ecosystem functioning. Until such evidence is available, health-related claims remain exploratory. Risks should also be carefully assessed: although common houseplants in moderate numbers present limited allergenic effects [142], extensive vegetation in disturbed or poorly managed soils may promote opportunistic or pathogenic taxa, as these environments often support fewer beneficial symbionts and more plant pathogens [152].

Key take-home messages: (i) Plants maintain ecological connections with their environment through continuous microbial exchange. (ii) plants host diverse microbial communities that are mostly neutral or beneficial to human health, with few pathogens. (iii) plants function as microbial hubs, supporting stable localised microbial ecosystems.

Research gaps remain on: (i) Whether plant-associated microbial communities maintain diversity and functionality under prolonged indoor conditions. (ii) composition, overlap, and interactions of species-specific plant microbiomes with other indoor microbial assemblages. (iii) how plant-associated microbes contribute to indoor ecosystem stability and resilience. (iv) how specific plant-associated microbial taxa can reduce human health risks. (v) potential risks from introducing vegetation or soils, including allergenic impacts.

TC3, 'human health and wellbeing' (Q7, Q4), addresses the overarching question: How does iGI directly influence the health, well-being, and performance of people indoors?

2.7 Q7. How does iGI affect building user/resident cognition, emotion, physiology, and overall health and wellbeing?

Architecture must move beyond regulating parameters such as temperature and humidity, adopting a holistic approach that includes physical, cognitive, and social dimensions of well-being. The UK Government’s Foresight project identified five key actions for promoting well-being - connecting with others, being physically active, staying mindful, learning, and giving, which align with architectural strategies that encourage social interaction and mental engagement [153]. However, the focus on energy efficiency after the 1970s oil crisis led to sealed buildings that limited natural light and ventilation, reducing indoor air quality and contributing to sick building syndrome (SBS), a condition associated with discomfort, reduced productivity, and increased healthcare costs [153,154].

iGI, understood as the incorporation of natural elements and biophilic principles (such as potted plants and indoor green walls) within built spaces, has emerged as a potential strategy for enhancing productivity, mental health, and overall well-being [154–156]. Its benefits are underpinned by two complementary mechanisms: physiological improvements in IEQ (see Q1–Q4) and psychological restoration, defined as the recovery from stress and mental fatigue [157]. Accordingly, Q7 focuses on non-thermal human outcomes associated with indoor greening, cognitive performance, affective responses (e.g., stress and mood), physiological stress markers (e.g., heart rate, cortisol, EEG/EDA where reported), and behavioural interaction with space, drawing on restorative and biophilic theories. Thermal sensation/acceptability outcomes and thermostat/setpoint implications are addressed in Q4 to avoid conflating distinct measurement frameworks and design implications.

Psychological restoration is guided by two main theories. Stress Reduction Theory suggests that seeing unthreatening nature elicits an effective response, which allows for the recovery of psychological and physiological functions related to arousal [158]. Attention Restoration Theory suggests that nature requires effortless attention, allowing the directed attention resources, needed for concentration, to rest and restore [159,160].

Recent conceptual work by Altomonte et al. (2024) further extends these theoretical models by situating restorative and affective responses within a broader temporal and multidimensional framework of wellbeing [161], distinguishing short-term physiological and psychological recovery from longer-term cognitive, behavioural, and social adaptations within the built environment [161]. Building on these theoretical mechanisms, empirical studies have explored how iGI influences health and well-being in residential, workplace, educational, and care environments (Table S6). Reported outcomes are generally classified into cognitive, affective, and physiological domains. Figure 8 synthesises the current evidence, illustrating the main cognitive, affective, and physiological pathways through which indoor greening contributes to psychological restoration, productivity, and wellbeing. Overall, current evidence shows modest benefits for mood, productivity, and physiological relaxation across diverse settings.

With respect to the cognitive domain, meta-analyses indicate modest t gains in students' academic performance and response times, following exposure to iGI environments when compared with conventional indoor settings lacking natural elements [34]. Nevertheless, systematic reviews associate iGI with enhanced productivity and perceived performance [41,162]. With respect to the affective domain, experimental studies have shown that visual exposure to natural elements can evoke calmer physiological responses and positive emotional states, including stress reduction. These findings suggest that the direct proximity of plants can produce small, but statistically reliable effects on sick leave [162]. Direct contact with plants, flowers, and natural materials such as wood has been associated with reduces anxiety and increased perceptions of calm, safety, and comfort [155,163]. These spaces have been linked to perceptions of emotional attachment and connectedness between users and their surroundings [164], this suggests that indoor greenery may play a supportive role, beyond aesthetic considerations, in shaping occupants' psychological experiences, including aspects of well-being, perceived productivity, and quality of life. Physiological evidence reinforces these findings, as iGI exposure is associated with lower heart rate, decreased cortisol, and higher alpha brain activity [40,165–167]. Combined, these results suggest that indoor greenery mitigates stress and enhances emotional stability.

Researchers have increasingly combined psychological and behavioural approaches to capture how users perceive and interact with indoor greenery. Qualitative methods such as interviews, focus groups, and photovoice offer insights into emotional and perceptual responses [168–170].

Standardised frameworks, such as COM-B, further illustrate how iGI influences perceptions of capability, opportunity, and motivation [171], while observational tools like MOHAWK enable the systematic analysis of user-environment interactions in real settings [3]. Together, these complementary approaches provide a richer understanding of iGI impacts by connecting subjective experiences with observable behaviour.

Key take-home messages: (i) Indoor greening may enhance cognitive, emotional, and physiological health and well-being; (ii) effects arise from physiological IEQ improvements and psychological restoration; (iii) Evidence shows modest gains in mood, productivity, and relaxation across settings, though stronger proof is needed; (iv) Visual and tactile contact with plants promotes emotional stability, social connection and belonging.

Research gaps remain on: (i) long-term assessments of iGI effects on productivity, mental health, and well-being, including how benefits change over time; (ii) studies across diverse cultural, climatic, and socio-economic contexts beyond labs or single cases; (iii) systematic exploration of multisensory biophilic exposure - visual, tactile, olfactory, and acoustic - in indoor and semi-outdoor settings; (iv) comprehensive cost-benefit analyses to inform large-scale implementation and policy; (v) in-depth study of semi-outdoor spaces’ impact on comfort and social interaction; (vi) integration of environmental justice perspectives to ensure equitable iGI benefits for vulnerable groups. Addressing these gaps will expand biophilic design’s applicability, reinforce its evidence base, and consolidate architecture’s role in health, well-being, and equity.

TC4, ‘Equity, access, and socio-economic impact’ (Q8), addresses the overarching question: What evidence exists for using iGI to improve IEQ among socially vulnerable groups?

2.8 Q8. How might iGI improve IEQ for socially vulnerable groups facing disadvantages

(low income, poor quality of housing, crowding)?

Social vulnerability factors can result in stress, isolation, and exposure to poor IEQ [172] through structural inequities including poorly maintained residential, work, education and healthcare settings, presence of hazardous materials (e.g., asbestos and formaldehyde), proximity to outdoor pollution, use of indoor solid fuel stoves, or containing animal frass, dampness, mould, or over-crowding [173–177], leading to excess exposures to indoor VOCs, carbon dioxide, carbon monoxide, and particulate matter. Socioeconomic status, racial or ethnic discrimination, disability, and advanced age may also limit the availability and quality of HVAC, where limited air exchange may contribute to excess indoor pollutants exposure [173,174,178].

iGI has the potential to modify the relationship between IEQ and social vulnerability factors (Table S7). Previous research on indoor greening has mainly demonstrate that iGI can affordably enhance air quality, humidity balance, and psychological comfort (see Q1–Q5; [179]). Studies examining iGI in socially vulnerable or low-income populations remain scarce [180] but suggest potential benefits. A recent review found that plants in post-operative settings reduced anxiety, stress and improved recovery [36]. Greening solutions co-created with residents and nursing staff, incorporating building physics data, were tested in the context of individualised approaches to improved comfort [181]. Resident interviews suggested a positive effect of greening on well-being, although this perception was not substantiated by measures of indoor air quality. A review of the relationship between greening and well-being highlighted that patients in healthcare facilities experienced improved psychological and physiological conditions, including enhanced cognition [29]. A survey of older adults revealed preferences for gardens (both indoor and outdoor), green walls/vertical gardens, and air-purifying vegetation, while finding iGI features less effective than lighting or ventilation for evoking natural environments. [174]. Study participants designated as socioeconomically vulnerable showed a significant preference for vertical gardens. Tomkins et al. (2019) demonstrate how home and community gardens enhanced wellness in a Syrian refugee camp situated in northern Iraq [182]. Planting directly outside tents, including green walls, provided badly needed cooling in tents that otherwise exceeded 50°C. With a highly vulnerable population lacking the means to earn their own money or autonomy over day-to-day decisions, gardens constructed alongside tents, on streets, and in common areas provided a sense of placemaking and resilience to many refugees, while other refugees rejected gardens as a sign of permanent acceptance of refugee status. These results underscore that vulnerable populations, like any other, hold a range of experiences and opinions.

Key take home messages: (i) socially vulnerable groups often face poorer IEQ due to low-quality housing, inadequate ventilation, and pollutant exposure; (ii) iGI offers affordable, small-scale interventions to improve thermal comfort, air quality, and psychological well-being; (iii) effectiveness depends on environmental factors like light, temperature, ventilation, and community involvement in design and upkeep; (iv) beyond physical benefits, iGI supports placemaking, emotional resilience, and social cohesion; (v) evidence is limited, underscoring the need for community-based research to ensure equitable, context-sensitive implementation.

Research gaps remain on: (i) understanding how iGI modifies exposure-response pathways between indoor pollutants, thermal stress, and health across different socioeconomic and demographic groups; (ii) conducting long-term, community-based field studies in diverse housing and climates; (iii) evaluating accessibility, affordability, and maintenance requirements of iGI for vulnerable users; (iv) integrating participatory design and behavioural research to ensure culturally appropriate, equitable implementation.

TC5, 'implementation and systems integration' (Q9, Q10, Q3), addresses the overarching question: What are the real-world barriers and solutions for implementing iGI at scale?

2.9 Q9. What types of iGI physical interventions currently exist for IEQ, and for what specific purposes are they implemented?

iGI are commonly placed indoors in living and working spaces, providing multifaceted benefits that encompass a continuum of interventions ranging from small plantings to large greenery and engineered infrastructures. Previous questions (Q2-Q4) have demonstrated the effects of indoor plants on IEQ and reduction of building energy consumption; however, research that systematically frames, categorises, and contextualises currently available iGI physical interventions remains scarce. Accordingly, this section adopts a framework-oriented perspective, focusing on how different iGI typologies are conceptually positioned, the functional purposes they are designed to serve, and how their degree of technological integration governs their interaction with indoor environmental processes. This approach provides a consistent structural basis for interpreting performance evidence discussed elsewhere in the review and avoids repetition of results presented in earlier questions. The classification of green systems typologies often follows several criteria, including plant species (function distinctively to provide diverse benefits), planting mobility, and growing media. However, for comparability on iGI operating within buildings (based on installation and maintenance requirements), we proposed to group current typologies according to their degree of technological integration and the mode of ecological-mechanical interaction with the indoor environment (See Figure 1): (1) passive planting (self-contained and non-engineered plants, i.e. potted plants and hanging plants); (2) vertical greenery (passive and vertically integrated systems, i.e. green façades and green wall); (3) aquatic systems (plants with visible water features, i.e. aquaponic walls and decorative water gardens); (4) hydroponic system (engineered water–nutrient circulation, i.e. vertical farming and recirculating hydroponic); (5) hybrid interventions (plants with active airflow or filtration, i.e. active botanical biofilters) and (6) space-scale planting (large and spatially integrated greenery, i.e. balcony planter and floor-integrated systems). Each of these interventions is often deployed with overlapping goals that aim to achieve an optimisation in IEQ and human well-being [183]. In addition to the above benefits, the appropriate use of iGI design can reduce HVAC load and energy consumption (Q3) [184]. Therefore, comprehensively investigating iGI physical interventions types warrants greater attention to achieve healthy and sustainable buildings.

From a typological and deployment perspective, the degree of empirical evidence available for different iGI interventions reflects their maturity and practical feasibility rather than direct performance ranking. Among iGI interventions, field evidence is greatest for passive and semi-active typologies (e.g., green walls, balcony planters); conversely, aquatic plants and hydroponic systems remain under-evaluated (Figure 9). While active botanical biofilters achieve impactful IEQ optimisation, their technologically capable, practical integration and maintainability remain complex [185]. For instance, moisture management, substrate and filter/pump maintenance to ensure the persistence of healthy plants, and the continuous monitoring of associated microbial communities to avoid performance drift [186,187]. Hydroponic and aquatic systems also require high initial cost and maintenance requirements [188], (i.e. electrical conductivity/pH control). The ease of maintenance for space-scale planting and passive green walls with vascular plants is moderate, requiring dependable irrigation and fertilisation (e.g. fertigation), proper indoor climate conditions, etc (see Q10). Conversely, passive planting and passive green walls with non-vascular plants (i.e mosses and liverworts), have the lowest complexity for general maintenance [189], including routine watering/fertilising, and occasional pruning or repotting.

Table 4 extends the scope of previous questions (Q1-Q4) by discussing IEQ benefits of iGI from the macro perspective. This table provides an overview of related studies, outlining the effectiveness and main purposes of the proposed classification of iGI typologies, and their degree of maturity levels available. Further details related to their separate benefits and maturity levels are described in Section S1. These studies (Figure S1) concluded that, (i) a substantial literature has focused on iGI's air quality improvements; (ii) active botanical biofilters show the most robust IAQ optimisation (VOCs, PM, CO_2) relative to other iGI under forced airflow; (iii) large vertical greenery can reduce PM concentrations and noise; (iv) hydroponics system with high photosynthetic leaf-area and adequate lighting deliver measurable local CO_2 reductions; (v) thermal/humidity regulation of iGI is modest, but integrating with HVAC can maximise their impact (Q3 and Q4); (vi) field evidence on aquatic and hydroponic systems indoors are limited; (vii) and space-scale planting can provide a shading effect to mitigate heat (Q4 and Q8) and alter incoming airflow.

Key take home messages includes: (i) A mature iGI typology exists, but lacks a comprehensive classification of available interventions; (ii) active botanical biofilters offer the highest IAQ improvements (PM and VOCs removal), while passive green walls provide similar air filtration plus sound absorption benefits; (iii) thermal and humidity regulation effects are modest but can yield energy and IEQ co-benefits when combined with HVAC; (iv) efficacy depends on factors such as species, substrate, planting volume, ventilation, lighting and maintenance.

Research gaps remain on: (i) validating findings in actual buildings and across spatial scales; (ii) addressing maintenance burdens and performance decline over time; (iii) exploring aquatic plants and hydroponic systems; (iv) assessing IEQ benefits, which may be negligible without substantial planting affecting room-level concentrations. Future work should prioritise standardised, in-situ trials across building types, quantify impacts at room and building scales under realistic ventilation, evaluate seasonality, maintenance, microbiological safety, and cost-effectiveness to inform scalable adoption. Studies should examine real-world plant care and whether more or denser iGI can effectively lower pollutants and be practical to maintain.

2.10 Q10. What are the major engineering barriers to deploying indoor greening?

Engineering and operational barriers remain key obstacles to the widespread deployment of iGI systems. Despite their demonstrated environmental and wellbeing benefits, implementation is often hindered by technical complexity, structural limitations, and the absence of clear design and maintenance standards. Together, they contribute to uncertainty and reluctance among owners and facility managers to adopt iGI, as the engineering requirements for safe integration, reliable operation, and long-term maintenance are often complex and poorly defined [47,198]. Evidence from previous studies shows that such challenges cut across design, installation, and long-term operation are further compounded by building-type specific constraints (Table S8).

Structural and spatial limitations constrain the retrofitting of iGI systems into existing buildings, where limited load-bearing capacity, insufficient wall or floor space, and lack of integrated drainage pathways are common challenges [47,199]. Multi-storey retrofits are particularly problematic, as structural reinforcement and vertical water distribution add significant cost and complexity. Even in new buildings, spatial trade-offs between circulation, usable floor area, and greening installations can discourage adoption. These constraints often restrict iGI in residential contexts to small modular planters or lightweight walls, while larger commercial or institutional buildings can only accommodate such systems where sufficient space and structural provisions are planned during early design stages [200,201].

Integration with mechanical systems is another significant barrier to the adoption of iGI [47,200,202]. Poor coordination with HVAC infrastructure can lead to airflow disruption or condensation risks, particularly when installations obstruct diffusers or alter ventilation patterns [99,203]. Plumbing and irrigation create additional challenges: reliable water supply and drainage are costly to install and technically complex in multi-storey retrofits, while sensitive facilities such as museums often prohibit water infrastructure altogether [47]. Lighting integration is another concern. Many interiors lack daylight, requiring supplemental LEDs that raise electricity demand and HVAC loads. Designing plant lighting that avoids glare and complies with energy codes typically requires case-specific solutions [204].

Economic and operational burdens remain key obstacles to the widespread adoption of iGI systems. Installation costs for living walls are considerably higher than standard interior finishes, and annual maintenance alone can account for approximately 8% of the initial investment, meaning that total upkeep over a 10-year period may match or exceed the original capital cost (Riley, 2017). These challenges are particularly pronounced in active systems that incorporate irrigation pumps, lighting, and monitoring infrastructure, where skilled labour is required for routine pruning, pest control, and system troubleshooting. Maintenance demands such as clogged irrigation lines, nutrient build-up, and pump failures can significantly increase operational complexity and long-term costs, particularly in buildings without access to horticultural or facilities expertise [47,198,205,206]. Maintenance can also be hazardous: vertical systems often require staff to work at height in damp conditions, increasing safety risks [207].

To address these issues, several design optimisations have been proposed. Embedding greening systems within structural elements can reduce upfront costs, while modular and easily accessible configurations allow for simplified maintenance and faster interventions. Selecting hardy, slow-growing species and integrating efficient irrigation and monitoring systems can minimise replacement frequency, reduce water use, and ease the burden on facility staff. Without such strategies, indoor greening is likely to remain a high-end, bespoke intervention. However, when life-cycle cost, safety, and maintainability are considered from the outset, iGI can evolve into a scalable, robust, and serviceable component of mainstream building design.

A cross-cutting barrier is the absence of clear technical standards and regulatory frameworks. Unlike structural or electrical systems, iGI lacks codified load calculations, waterproofing guidelines, or fire performance classifications. This results in inconsistent practices and complicates approvals. Fire codes rarely address living wall assemblies, leaving regulators to make case-by-case decisions, discouraging adoption in risk-averse institutions [208]. Similarly, without certification protocols, claims about energy savings or indoor air quality improvements remain anecdotal, undermining investment [209].

These barriers manifest differently across building types as illustrated in Figure 10. Residential buildings face the steepest feasibility issues, limited structural capacity, no integrated plumbing, and a lack of skilled maintenance, restricting iGI to small planters or modular walls [199]. Commercial buildings have greater resources, but require careful HVAC and plumbing integration, and often depend on professional maintenance contracts to reduce liability. Institutional buildings, such as schools and hospitals, present the strictest fire, infection-control, and budgetary requirements, often limiting greening to enclosed or low-risk displays [47,209].

Key take home messages: (i) engineering barriers like load limits, lighting constraints, and HVAC conflicts restrict large-scale iGI deployment; (ii) maintenance, water management, and safety risks increase long-term costs and limit reliability; (iii) lack of standards for fire safety, waterproofing, and structural performance discourages adoption; (iv) early multidisciplinary coordination and innovation in lightweight, smart, low-maintenance systems are essential for mainstream implementation.

Research gaps remain on: (i) developing validated load and durability models for vertical and modular systems; (ii) co-simulating HVAC-iGI interactions to prevent humidity conflicts; (iii) quantifying lifecycle costs and maintenance impacts; (iv) creating unified technical standards and certification protocols. Beyond engineering barriers, persistent non-technical barriers, including social acceptance and unclear liability and ownership of maintenance responsibilities, continue to limit iGI uptake in practice. Addressing these combined technical and non-technical will shift iGI from bespoke designs to standardised building services, enhancing health and sustainability outcomes.

3. Discussion

The discussion on the above ten questions reveals critical quantitative gaps in indoor greening research. A matrix (Figure 11) synthesises the available quantitative evidence and expert judgment, intended to be indicative rather than definitive, including on the available data confidence, to translate the conceptual synthesis from Q1–Q10 into a systematic comparison framework. Details of the development of the matrix are included in SI Section S2, and the iGI type category in the matrix are grouped in accordance with the classification discussed in Q9, that iGI types are namely: (1) passive planting; (2) vertical greenery; (3) aquatic systems; (4) hydroponic system; (5) hybrid interventions and (6) space-scale planting. Each indicator corresponds to one or more of the ten questions, collectively capturing how iGI systems interact with indoor environmental, biological, psychological, and technical dimensions of performance. Data-availability scores show marked differences in the current evidence base (Figure S1). Research is comparatively well developed for VOC and PM removal, humidity regulation, thermal comfort, and mental wellbeing, although results remain heterogeneous and strongly context-dependent, reflecting decades of research on plant–environment interactions and human biophilic responses. Evidence on productivity and attention benefits is growing, but remains uneven and sensitive to experimental design, particularly for passive plants and indoor gardens. Several domains remain underexplored: Robust empirical data are limited for CO_2 modulation, noise absorption, HVAC and energy synergies, and the microbial implications of iGI, including bioaerosol generation, mould risk, and microbial community dynamics, with many studies relying on laboratory or short-term observations. Evidence is particularly sparse for aquatic, hydroponic, and space-scale planting systems (Q9), where most indicators draw on only a small number of studies. Current literature often shows a positive bias towards the beneficial effects of iGI, with comparatively fewer studies reporting null results or system failures. This tendency leaves a gap in understanding the circumstances under which iGI may have neutral or even adverse impacts. The matrix reinforces this by showing low confidence levels for several indicators, especially pollutant removal, microbial diversity, and bioaerosol risks, suggesting that these findings should be interpreted with caution. Future research addressing these less-explored aspects, such as suboptimal maintenance, inadequate lighting, or unintended effects on indoor air quality, would provide a more balanced and comprehensive view of their real-world performance.

Beyond data availability, the matrix highlights a performance-complexity continuum reflecting interdependencies throughout the ten-question framework. As iGI systems progress from passive to active, their capacity to influence air quality, humidity regulation and thermal comfort increases, but available evidence suggests substantial variability in both direction and magnitude of effects, particularly for air quality in real-world environments, remain uncertain, while operational demands, energy use and maintenance requirements also rise (Q1, Q3). Passive green walls provide low to medium VOC removal and medium RH moderation, while active biofilters deliver moderate PM and VOC reduction and consistent humidity balance, enhancing thermal comfort (Q1–Q4). However, CO_2 modulation remains consistently low across nearly all typologies, highlighting that most iGI systems cannot compensate for inadequate ventilation. This confirms that technological integration and controlled airflow may enhance certain aspects of IEQ under certain conditions (Q9–Q10).

Performance data from Q2 shows how environmental conditions affect system efficiency. Passive planters tolerate variable light but are only modestly sensitive to high ventilation rates that diminish their impact. In contrast, hydroponic and aeroponic systems require intense artificial lighting and continuous irrigation to thrive. iGI effectiveness depends not just on system type but on compatibility with the surrounding environment. Without proper control, systems experience stress and reduced thermal and humidity performance, indicating that performance gains are contingent on careful design, operation, and maintenance, confirming optimisation challenges identified in Q5.

At the system level, the matrix connects HVAC/energy synergy, bioaerosol and mould risk, and IoT readiness to interaction between Q3 and Q5. Active biofilters and duct-integrated modules achieve moderate ventilation synergy and deliver limited energy savings when combining air recirculation with biological filtration. Hydroponic vertical farming systems also show comparatively high IoT/control readiness, indicating that technological sophistication is not limited to active biofiltration approaches. However, the biological activity that improves air treatment also increases mould risk to moderate levels and is associated with non-negligible bioaerosol risk, although empirical evidence remains limited across system types. Moderate IoT-readiness scores reflect the growing importance of sensor-based feedback and automated regulation to stabilise environmental conditions and prevent contamination under varying humidity and temperature. Space-scale installations like atria and winter gardens achieve a mixed performance profile, providing modest to moderate benefits across physical and social dimensions with moderate maintenance needs. Across these larger typologies, integration difficulty remains moderate, reflecting structural constraints and irrigation requirements. Such intermediate solutions balance the performance advantages of active systems with the accessibility of passive approaches (Q3, Q5, Q8).

The socio-technical indicators in Q8–Q10 reveal tensions between sophistication and accessibility. Small and medium passive planters show high equity and accessibility with very high maintainability, making them suitable for diverse environments, including resource-constrained housing. Smaller passive green walls, though moderate in maintenance effort, remain reasonably accessible and cost-effective compared to active or hydroponic systems. In contrast, advanced systems such as active biofilters, hydroponic towers, and aquaponic walls score low and moderate in accessibility and equity, reflecting higher cost and technical barriers. Field evidence and maturity levels are highest for passive planters and certain passive green wall systems, while hydroponic and aquaponic systems remain in early-to-intermediate validation stages. This pattern confirms findings in Q9 and Q10, which identify maintainability, accessibility, integration complexity, and technical regulation as the main barriers to widespread implementation.

The physiological, psychological, and ecological dimensions outlined in Q4, Q6 and Q7 highlight iGI's dual impacts on human well-being and indoor ecological dynamics. Vegetation can enhance thermal comfort and perceived freshness through modest to moderate humidity regulation and biophilic cues, potentially allowing for wider acceptable temperature ranges. Almost all typologies deliver moderate to high stress reduction and wellbeing benefits, primarily based on self-reported or short-term experimental evidence, suggesting that greenery provides psychological benefits regardless of measurable air quality improvements. Productivity and attention benefits differ between typologies, with passive planters showing consistently higher scores than passive green walls. Productivity and attention enhancements are generally modest, with effects that appear sensitive to context, task type, and exposure duration, but increase in immersive installations like atria and winter gardens.

The matrix establishes an initial roadmap for designing and evaluating indoor greening systems within next-generation energy-efficient and health-oriented building environments. It confirms that iGI effectiveness depends not just on technology, though technological integration enhances specific biophysical functions, but on alignment between design intent, environmental context, and user interaction. This shifts the discussion from "whether" indoor greening improves IEQ to "how" it performs under different physical, biological, and social conditions, and under which circumstances such performance may be limited, neutral, or counterproductive.

4. Conclusions

The ten questions in this paper examine the role of iGI in shaping healthier, more sustainable, and climate-resilient indoor environments. By systematically examining iGI through biophysical, ecological, human, and socio-technical perspectives, the framework integrates fragmented evidence from disciplines that have traditionally studied air quality, comfort, and wellbeing in isolation.

Beyond the key messages and research gaps identified for each question, the following conclusions emerge from the five thematic clusters.

TC1. Biophysical and technical performance (Q1–Q5): Indoor greening can influence IEQ through biophysical, psychological and technical processes, including humidity regulation, pollutant removal and heat exchange. Plants help moderate indoor temperature and humidity and may reduce gaseous and particulate pollutants through deposition, filtration, and microbial degradation (Q1). The effectiveness of these processes depends on environmental factors like light intensity, substrate moisture and nutrient status, plant density, and ventilation rates, which affect plant physiological activity and measurable IEQ improvements (Q2). Integrating iGI with HVAC systems can enhance thermal and air-quality stability but involves trade-offs like increased energy consumption and maintenance (Q3). Psychological benefits linked to biophilia further enhance occupant comfort beyond measurable environmental changes (Q4). Emerging technologies like IoT-sensing, machine learning, and digital twins enable predictive monitoring and automated control (Q5), addressing prior barriers by optimising system performance and preventing microbial growth. Challenges remain in sensor accuracy, data integration, cost, and standardisation must be addressed for full implementation. Overall, iGI has the potential to act as a living environmental moderator that is technically feasible, but requires refined engineering for consistent performance. However, the magnitude and repeatability of these IEQ benefits remain uncertain across building types and ventilation regimes, and stronger in-situ, long-term evidence is needed. Future work should prioritise standardised field trials and mechanistic/predictive models that quantify how species, planting density, lighting, watering and ventilation jointly determine reliable IEQ outcomes and associated energy trade-offs.

TC2. Ecological and microbiological dynamics (Q5–Q6): iGI shapes indoor microbial ecology by potentially introducing beneficial plant-associated microbiota and moderating bioaerosol risks. Predictive modelling and control systems can identify microbial thresholds to prevent mould growth, supporting risk management and early warning (Q5). Plants stabilise and enrich indoor microbial communities, possibly influencing pathogen dynamics, though these effects require further study (Q6). Indoor plant microbiology and its human health impacts remain under-researched, particularly regarding l ecosystem stability, species-specific dynamics, and the functions of plant-associated microbes. Balancing microbial enrichment with hygiene management through intelligent control systems is essential to prevent harmful bioaerosol proliferation. Nonetheless, evidence on the stability, functionality, and health relevance of plant-associated indoor microbiomes remains limited, and causal links to health outcomes are still uncertain. Future research should combine longitudinal microbiome monitoring, species-/substrate-specific comparisons, and risk assessment to determine when microbial enrichment benefits versus when hygiene controls are needed.

TC3. Human health and well-being (Q4, Q7): Indoor greening may positively affect well-being through biophysical and psychological mechanisms. Improved humidity and thermal conditions improve comfort, while natural elements can reduce stress and promote cognitive performance and emotional wellbeing (Q4, Q7). These benefits align with Restoration theories, highlighting biophilic exposure’s role in recovery and social connectedness. While short-term benefits are well documented, long-term and multisensory effects across diverse contexts need research. Effect sizes and persistence remain uncertain beyond short-term studies, and evidence varies across building types and populations. Future work should prioritise long-term and multisensory exposure pathways alongside practical trade-offs like maintenance or allergen risks.

TC4. Equity, access, and socio-economic impact (Q8): Indoor greening can reduce IEQ inequalities by improving comfort and well-being in disadvantaged communities. Low-income and ageing populations often experience poorer IEQ due to inadequate housing, limited ventilation, and pollutant exposure. iGI could mitigate these conditions through humidity control, pollutant reduction, and restorative benefits. However, most applications focus on affluent or institutional contexts, leaving marginalised groups underrepresented in both research and implementation. Co-created designs integrating local preferences and cultural values can expand accessibility while fostering community ownership. Future policies must prioritise affordability, maintenance capacity, and inclusivity, positioning iGI as both a technical and social tool to reduce indoor environmental health disparities.

TC5. Implementation and systems integration (Q3, Q9, Q10): Scalable iGI deployment requires overcoming technical challenges including structural constraints, HVAC integration, and maintenance demands (Q10). Despite field evidence of IEQ benefits (Q9), lack of standardised metrics and certification limits replication and investor confidence. Successful integration into building management systems demands collaboration among architects, engineers, and horticulturists to ensure safety, energy efficiency, and sustainability (Q3, Q10). Innovations, including lightweight substrates, modular designs, and smart irrigation systems, offer pathways to automation and reduced operational demands. Establishing international technical standards (similar to green roof standards) is vital for regulatory acceptance and market growth, including standardized protocols for lifecycle cost evaluation and safety assessment to support investment confidence and deployment. Uncertainties remain regarding durability of benefits under realistic ventilation and performance decay across different iGI typologies. Mainstreaming iGI requires evidencing conditions where it delivers benefits in real buildings.

Future research should move beyond isolated lab studies toward integrated, data-driven approaches linking plant physiology, building engineering, and occupant health. The current evidence base remains uneven across building types, climates, and user groups, with limited long-term validation. Studies should prioritise standardised field protocols, longitudinal monitoring and predictive modelling to quantify performance, energy trade-offs, and safety under realistic conditions. This paper provides a cross-disciplinary framework to guide when, where, and how iGI can deliver measurable benefits in real buildings, and where key uncertainties remain.

4. Acknowledgements

This work has been carried out under the framework of UKRI (EPSRC) funded GREENIN Micro Network Plus (Grant No. APP55977) and the UGPN-funded tri-lateral (UK, USA, Brazil) GREENICON project.

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6. Declaration of competing interests

The authors declare that they have no known competing financial interests or personal interests or personal relationships that could have appeared to influence the work reported in this paper.

7. Data availability

No data was used for the research described in the article.

8. References

[1] B.L. Diffey, An overview analysis of the time people spend outdoors, British Journal of Dermatology 164 (2011) 848–854.

[2] L. Morawska, J. Allen, W. Bahnfleth, B. Bennett, P.M. Bluyssen, A. Boerstra, G. Buonanno, J. Cao, S.J. Dancer, A. Floto, Mandating indoor air quality for public buildings, Science 383 (2024) 1418–1420.

[3] M.L. Benton, A. Abraham, A.L. LaBella, P. Abbot, A. Rokas, J.A. Capra, The influence of evolutionary history on human health and disease, Nature Reviews Genetics 22 (2021) 269–283.

[4] C. Sarkar, C. Webster, Urban environments and human health: current trends and future directions, Current Opinion in Environmental Sustainability 25 (2017) 33–44.

[5] P. Wallner, U. Munoz, P. Tappler, A. Wanka, M. Kundi, J.F. Shelton, H.-P. Hutter, Indoor environmental quality in mechanically ventilated, energy-efficient buildings vs. conventional buildings, International Journal of Environmental Research and Public Health 12 (2015) 14132–14147.

[6] P. Kumar, K.C. Perez, A. Biswal, H. Sun, A.K. Dwivedi, S. Hama, S. Khalili, A. Ahlawat, M. De Fatima Andrade, R.A. Alves, E.A. Amaral Dos Santos, M. Athanassiadou, C.B. Ribeiro, P. Bhusal, M.L. Bucalem, B.G. Buchanan, L.F. Candido, S.-J. Cao, A.L. Casteli Figueiredo Gallardo, R. Chang, A.K. Chaves Ribeiro, B. Considine, R. Maura De Miranda, L. Aparecida De Paiva, P. De Souza, M.A. Franco, E.D. Freitas, H.C. Frey, M.F. Funari, B. Furieri, J. Gallagher, L.L. Giatti, M.J. Goroski Rambalducci, C.H. Halios, F. Haris, L. Hoinaski, C. Horton, Y. Huang, L. Jones, R. Jones, J. Kandulu, M. Katti, G.M. Locosselli, A.A. Lucchezi Miyahara, J.A. Martins,

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[7] P. Kumar, S.E. Debele, S. Khalili, C.H. Halios, J. Sahani, N. Aghamohammadi, M.D.F. Andrade, M. Athanassiadou, K. Bhui, N. Calvillo, S.-J. Cao, F. Coulon, J.L. Edmondson, D. Fletcher, E. Dias De Freitas, H. Guo, M.C. Hort, M. Katti, T.R. Kjeldsen, S. Lehmann, G.M. Locosselli, S.K. Malham, L. Morawska, R. Parajuli, C.D.F. Rogers, R. Yao, F. Wang, J. Wenk, L. Jones, Urban heat mitigation by green and blue infrastructure: Drivers, effectiveness, and future needs, The Innovation 5 (2024) 100588. https://doi.org/10.1016/j.xinn.2024.100588.

[8] P. Kumar, K. Corada, S.E. Debele, A.P.M. Emygdio, K. Abhijith, H. Hassan, P. Broomandi, R. Baldauf, N. Calvillo, S.-J. Cao, S. Desrivières, Z. Feng, J. Gallagher, T.R. Kjeldsen, A.A. Khan, M. Khare, S.H. Kota, B. Li, S.K. Malham, A. McNabola, A. Namdeo, A.K. Nema, S. Reis, S.N. Sm, A. Tiwary, S. Vardoulakis, J. Wenk, F. Wang, J. Wang, D. Woolf, R. Yao, L. Jones, Air pollution abatement from Green-Blue-Grey infrastructure, TIG 2 (2024) 100100. https://doi.org/10.59717/j.xinn-geo.2024.100100.

[9] P. Kumar, J. Sahani, K. Corada Perez, A. Ahlawat, M.D.F. Andrade, M. Athanassiadou, S.-J. Cao, L. Collins, S. Dey, S. Di Sabatino, C.H. Halios, F. Harris, C. Horton, L. Inostroza, L. Jones, T. Rodding Kjeldsen, B. McCallan, A. McNabola, R. Kumar Mishra, S. Kumar Mishra, E.G. Sperandio Nascimento, G. Owen, K. Ravindra, N.C. Reis, V. Soebarto, J. Wenk, H.S. Wood, R. Yao, Urban greening for climate resilient and sustainable cities: grand challenges and opportunities, Front. Sustain. Cities 7 (2025) 1595280. https://doi.org/10.3389/frsc.2025.1595280.

[10] T.A. Moya, A. van den Dobbelsteen, M. Ottelé, P.M. Bluyssen, A review of green systems within the indoor environment, Indoor and Built Environment 28 (2019) 298–309. https://doi.org/10.1177/1420326X18783042.

[11] J. Sundell, H. Levin, W.W. Nazaroff, W.S. Cain, W.J. Fisk, D.T. Grimsrud, F. Gyntelberg, Y. Li, A.K. Persily, A.C. Pickering, Ventilation rates and health: multidisciplinary review of the scientific literature, Indoor Air 21 (2011) 191–204.

[12] P. Wargocki, D.P. Wyon, Ten questions concerning thermal and indoor air quality effects on the performance of office work and schoolwork, Building and Environment 112 (2017) 359–366.

[13] A. Toyoda, Y. Shibata, Y. Matsuo, K. Terada, H. Sugimoto, K. Higashi, H. Mori, A. Ikeuchi, M. Ito, K. Kurokawa, Diversity and compositional differences of the airborne microbiome in a biophilic indoor environment, Scientific Reports 13 (2023) 8179.

[14] H. Sun, C. Jimenez-Bescos, M. Mohammadi, F. Zhong, J.K. Calautit, Numerical investigation of the influence of vegetation on the aero-thermal performance of buildings with courtyards in hot climates, Energies 14 (2021) 5388. https://doi.org/10.3390/en14175388.

[15] G. Grant, D. Gedge, B. Cameron, Living Roofs and Walls from policy to practice, 10 years of urban greening in London and beyond, Published by the European Federation of Green Roof and Green Wall Associations (EFB) and Livingroofs. Org on Behalf of the Greater London Authority (2019) 256p.

[16] R. Aslanoğlu, J.K. Kazak, S. Szewrański, M. Świąder, G. Arciniegas, G. Chrobak, A. Jakóbiak, E. Turhan, Ten questions concerning the role of urban greenery in shaping the future of urban areas, Building and Environment 267 (2025) 112154. https://doi.org/10.1016/j.buildenv.2024.112154.

[17] M. Schweiker, R.K. Andersen, S. Carlucci, G. Chinazzo, S. Hodder, A. Mahdavi, B.I. Palella, A.L. Pisello, F.R. d'Ambrosio Alfano, M. Vellei, Ten questions concerning the usage of subjective assessment scales in research on indoor environmental quality, Building and Environment 283 (2025) 113393. https://doi.org/10.1016/j.buildenv.2025.113393.

[18] D. Booker, G. Petrou, L. Chatzidiakou, D. Das, F. Farooq, L. Ferguson, O.I. Jutila, K. Milczewska, M. Modlich, A. Moreno-Rangel, Ten questions concerning the future of residential indoor air quality and its environmental justice implications, Building and Environment 278 (2025) 112957.

[19] W.W. Nazaroff, Ten questions concerning indoor ultrafine particles, Building and Environment 243 (2023) 110641. https://doi.org/10.1016/j.buildenv.2023.110641.

[20] M. Awada, B. Becerik-Gerber, R. Liu, M. Seyedrezaei, Z. Lu, M. Xenakis, G. Lucas, S.C. Roll, S. Narayanan, Ten questions concerning the impact of environmental stress on office workers, Building and Environment 229 (2023) 109964.

[21] J. Taylor, R. McLeod, G. Petrou, C. Hopfe, A. Mavrogianni, R. Castano-Rosa, S. Pelsmakers, K. Lomas, Ten questions concerning residential overheating in Central and Northern Europe, Building and Environment 234 (2023) 110154.

[22] N. Ghaddar, K. Ghali, Ten questions concerning the paradox of minimizing airborne transmission of infectious aerosols in densely occupied spaces via sustainable ventilation and other strategies in hot and humid climates, Building and Environment 214 (2022) 108901.

[23] A. Steinemann, Ten questions concerning fragrance-free policies and indoor environments, Building and Environment 159 (2019) 106054.

[24] A.J. Hoisington, K.A. Stearns-Yoder, S.J. Schuldt, C.J. Beemer, J.P. Maestre, K.A. Kinney, T.T. Postolache, C.A. Lowry, L.A. Brenner, Ten questions concerning the built environment and mental health, Building and Environment 155 (2019) 58–69.

[25] A.J. Prussin II, D.O. Schwake, L.C. Marr, Ten questions concerning the aerosolization and transmission of Legionella in the built environment, Building and Environment 123 (2017) 684–695.

[26] A. Steinemann, P. Wargocki, B. Rismanchi, Ten questions concerning green buildings and indoor air quality, Building and Environment 112 (2017) 351–358. https://doi.org/10.1016/j.buildenv.2016.11.010.

[27] T. Hong, Y. Chen, X. Luo, N. Luo, S.H. Lee, Ten questions on urban building energy modeling, Building and Environment 168 (2020) 106508. https://doi.org/10.1016/j.buildenv.2019.106508.

[28] R.I. Adams, S. Bhangar, K.C. Dannemiller, J.A. Eisen, N. Fierer, J.A. Gilbert, J.L. Green, L.C. Marr, S.L. Miller, J.A. Siegel, Ten questions concerning the microbiomes of buildings, Building and Environment 109 (2016) 224–234.

[29] M. Paniccià, M. Acito, I. Grappasonni, How outdoor and indoor green spaces affect human health: a literature review, Annali Di Igiene Medicina Preventiva e Di Comunita (2024).

[30] S. Matheson, R. Fleck, P.J. Irga, F.R. Torpy, Phytoremediation for the indoor environment: a state-of-the-art review, Reviews in Environmental Science and Bio/Technology 22 (2023) 249–280.

[31] T. Zhao, I. Markevych, D. Buczyłowska, M. Romanos, J. Heinrich, When green enters a room: A scoping review of epidemiological studies on indoor plants and mental health, Environmental Research 216 (2023) 114715. https://doi.org/10.1016/j.envres.2022.114715.

[32] F. Fonseca, M. Paschoalino, L. Silva, Health and well-being benefits of outdoor and indoor vertical greening systems: a review, Sustainability 15 (2023) 4107.

[33] K. Ravindra, S. Mor, Phytoremediation potential of indoor plants in reducing air pollutants, Frontiers in Sustainable Cities 4 (2022) 1039710.

[34] K.-T. Han, L.-W. Ruan, L.-S. Liao, Effects of indoor plants on human functions: a systematic review with meta-analyses, International Journal of Environmental Research and Public Health 19 (2022) 7454.

[35] H. Samudro, G. Samudro, S. Mangkoedihardjo, Overview of indoor plants: phytoarchitecture as a building health platform, Journal of Design and Built Environment 22 (2022) 69–87.

[36] F. Liu, L. Yan, X. Meng, C. Zhang, A review on indoor green plants employed to improve indoor environment, Journal of Building Engineering 53 (2022) 104542. https://doi.org/10.1016/j.jobe.2022.104542.

[37] H. Samudro, S. Mangkoedihardjo, Indoor phytoremediation using decorative plants: An overview of application principles, Journal of Phytology 13 (2021) 28–32.

[38] S.G. Persiani, Benefits of using plants in indoor environments: Exploring common research gaps, Architecture 1 (2021) 83–98.

[39] S. Bandehali, T. Miri, H. Onyeaka, P. Kumar, Current state of indoor air phytoremediation using potted plants and green walls, Atmosphere 12 (2021) 473.

[40] K.-T. Han, L.-W. Ruan, Effects of indoor plants on air quality: a systematic review, Environmental Science and Pollution Research 27 (2020) 16019–16051.

[41] A. Aydogan, R. Cerone, Review of the effects of plants on indoor environments, Indoor and Built Environment 30 (2021) 442–460.

[42] L. Deng, Q. Deng, The basic roles of indoor plants in human health and comfort, Environmental Science and Pollution Research 25 (2018) 36087–36101. https://doi.org/10.1007/s11356-018-3554-1.

[43] B. Raji, M.J. Tenpierik, A. Van Den Dobbelsteen, The impact of greening systems on building energy performance: A literature review, Renewable and Sustainable Energy Reviews 45 (2015) 610–623.

[44] C. Gubb, T. Blanusa, A. Griffiths, C. Pfrang, Potted plants can remove the pollutant nitrogen dioxide indoors, Air Quality, Atmosphere & Health 15 (2022) 479–490.

[45] B.C. Wolverton, A. Johnson, K. Bounds, Interior landscape plants for indoor air pollution abatement, 1989.

[46] L. Pérez-Urrestarazu, R. Fernández-Cañero, A. Franco, G. Egea, Influence of an active living wall on indoor temperature and humidity conditions, Ecological Engineering 90 (2016) 120–124.

[47] K. Gunawardena, K. Steemers, Living walls in indoor environments, Building and Environment 148 (2019) 478–487.

[48] A.V. Arundel, E.M. Sterling, J.H. Biggin, T.D. Sterling, Indirect health effects of relative humidity in indoor environments., Environmental Health Perspectives 65 (1986) 351–361.

[49] E.R. Jones, J.G. Cedeño Laurent, A.S. Young, B.A. Coull, J.D. Spengler, J.G. Allen, Indoor humidity levels and associations with reported symptoms in office buildings, Indoor Air 32 (2022) e12961.

[50] B.E. Cummings, M.S. Waring, Potted plants do not improve indoor air quality: a review and analysis of reported VOC removal efficiencies, Journal of Exposure Science & Environmental Epidemiology 30 (2020) 253–261.

[51] F. Borzabadi Farahani, J. Rahimi, S. Khoramipour, E. Dehghanifard, M. Alimohammadi, Environmental modulation enhances benzene phytoremediation by Aglaonema and Dracaena in indoor settings, Scientific Reports 15 (2025) 31559.

[52] M.E. Bergman, X.-Q. Huang, S. Baudino, J.-C. Caissard, N. Dudareva, Plant volatile organic compounds: Emission and perception in a changing world, Current Opinion in Plant Biology 85 (2025) 102706.

[53] J. Ryu, J.J. Kim, H. Byeon, T. Go, S.J. Lee, Removal of fine particulate matter (PM2. 5) via atmospheric humidity caused by evapotranspiration, Environmental Pollution 245 (2019) 253–259.

[54] A. Katoch, U.C. Kulshrestha, Deposition of anthropogenic secondary anions through indoor dust on Ficus elastica plants in Delhi, India, Arabian Journal of Geosciences 17 (2024) 112.

[55] A. Katoch, U.C. Kulshrestha, Seasonal variations of dustfall fluxes and biochemical parameters in the foliage of selected indoor plants in Delhi, India, International Journal of Phytoremediation 25 (2023) 917–928.

[56] S. Yin, X. Zhang, A. Yu, N. Sun, J. Lyu, P. Zhu, C. Liu, Determining PM2. 5 dry deposition velocity on plant leaves: An indirect experimental method, Urban Forestry & Urban Greening 46 (2019) 126467.

[57] P.J. Irga, N.J. Paull, P. Abdo, F.R. Torpy, An assessment of the atmospheric particle removal efficiency of an in-room botanical biofilter system, Building and Environment 115 (2017) 281–290.

[58] J.A. Vorholt, Microbial life in the phyllosphere, Nature Reviews Microbiology 10 (2012) 828–840.

[59] F. Asdrubali, F. D'Alessandro, N. Mencarelli, K.V. Horoshenkov, Sound absorption properties of tropical plants for indoor applications, in: Proceedings of the 21st International Congress on Sound and Vibration, China, 2014.

[60] F. D'Alessandro, F. Asdrubali, N. Mencarelli, Experimental evaluation and modelling of the sound absorption properties of plants for indoor acoustic applications, Building and Environment 94 (2015) 913–923.

[61] J. Berger, E. Essah, T. Blanusa, C.P. Beaman, The appearance of indoor plants and their effect on people's perceptions of indoor air quality and subjective well-being, Building and Environment 219 (2022) 109151.

[62] J. Berger, E. Essah, T. Blanusa, The impact of plants on the humidity of naturally-ventilated office indoor environments, Journal of Building Engineering 86 (2024) 108814.

[63] E. Szczepańska-Rosiak, J. Sowa, K. Mastalerz, D. Heim, Useful daylight illuminance for ornamental plants in buildings–The method to design the green interior, Energy and Buildings 330 (2025) 115315.

[64] F.R. Torpy, P.J. Irga, M.D. Burchett, Profiling indoor plants for the amelioration of high CO2 concentrations, Urban Forestry & Urban Greening 13 (2014) 227–233.

[65] D. Marjorie, I.E. Buot Jr, R.D.R. Obeña, E.L.C. Villanueva, Ecology of Understory Plants of Forests Over Limestone in Samar Island, Philippines 11, Plant Diversity in Biocultural Landscapes (2023) 217.

[66] S.V. Pennisi, M.W. van Iersel, Quantification of carbon assimilation of plants in simulated and in situ interiorscapes, HortScience 47 (2012) 468–476.

[67] C. Gubb, T. Blanusa, A. Griffiths, C. Pfrang, Can houseplants improve indoor air quality by removing CO2 and increasing relative humidity?, Air Quality, Atmosphere & Health 11 (2018) 1191–1201.

[68] J. Hartmann, F. Feltrin, How to illuminate indoor plants sustainably? Tips and tricks to bridge the gap between research and design., in: IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2024: p. 012018.

[69] J. Jiang, P. Irga, R. Coe, P. Gibbons, Effects of indoor plants on CO2 concentration, indoor air temperature and relative humidity in office buildings, Plos One 19 (2024) e0305956.

[70] F.R. Torpy, M. Zavattaro, P.J. Irga, Green wall technology for the phytoremediation of indoor air: a system for the reduction of high CO2 concentrations, Air Quality, Atmosphere & Health 10 (2017) 575–585.

[71] F.R. Torpy, S. Matheson, G. Duani, L. Lyu, R. Fares, P.J. Irga, Rethinking urban horticulture: perspectives from applied biotechnology and environmental engineering, in: III International Symposium on Greener Cities: Improving Ecosystem Services in a Climate-Changing World (GreenCities2024) 1429, 2024: pp. 1–12.

[72] P.J. Irga, A. Morgan, R. Fleck, F.R. Torpy, Phytoremediation of indoor air pollutants from construction and transport by a moveable active green wall system, Atmospheric Pollution Research 14 (2023) 101896.

[73] C. Gubb, T. Blanusa, A. Griffiths, C. Pfrang, Interaction between plant species and substrate type in the removal of CO2 indoors, Air Quality, Atmosphere & Health 12 (2019) 1197–1206.

[74] L. Lyu, S. Matheson, R. Fleck, F.R. Torpy, P.J. Irga, Modulating phytoremediation: How drip irrigation system affect performance of active green wall and microbial community changes, Journal of Environmental Management 370 (2024) 122646.

[75] P.J. Irga, F.R. Torpy, M.D. Burchett, Can hydroculture be used to enhance the performance of indoor plants for the removal of air pollutants?, Atmospheric Environment 77 (2013) 267–271.

[76] W.W. Nazaroff, Residential air-change rates: A critical review, Indoor Air 31 (2021) 282–313.

[77] Z. Liu, C. Pfrang, R. Sommariva, J. Brean, Y. Su, W. Bloss, B. Fraga, A coupled fluids-chemistry model for pollutant dynamics indoors—Application to a kitchen scenario, Physics of Fluids 37 (2025).

[78] G. Petrou, E. Hutchinson, A. Mavrogianni, J. Milner, H. Macintyre, R. Phalkey, S.-C. Hsu, P. Symonds, M. Davies, P. Wilkinson, Home energy efficiency under net zero: time to monitor UK indoor air, BMJ 377 (2022).

[79] K.H. Conson, M. Li, V. Chan, A.C. Lai, Influence of mechanical ventilation system on indoor carbon dioxide and particulate matter concentration, Building and Environment 76 (2014) 73–80.

[80] I.Z. Ibrahim, W.-T. Chong, S. Yusoff, The design of the botanical indoor air biofilter system for the atmospheric particle removal, in: MATEC Web of Conferences, EDP Sciences, 2018: p. 02035.

[81] S. Abedi, S.-A. Somayeh, S. Behshad, A.J. Joneidi, R. Yarahmadi, Thermal effects, experimental evaluation of evaporative cooling performance and energy efficiency of active botanical biofilter for indoor air treatment, Journal of Building Engineering (2025) 112950.

[82] F. Liu, Q. Yuan, Y. Ren, X. Meng, Annual assessment of the active plant wall on indoor environment from summer, transition season and winter, Scientific Reports 15 (2025) 18198.

[83] Y. Yungstein, D. Helman, Cooling, CO2 reduction, and energy-saving benefits of a green-living wall in an actual workplace, Building and Environment 236 (2023) 110220.

[84] D. Zhang, L. Zhang, Y. Zhang, Investigation of the indoor CO2 removal efficiency and fresh air energy savings of living walls in office spaces, Journal of Building Engineering 90 (2024) 109422.

[85] Y. Shao, J. Li, Z. Zhou, Z. Hu, F. Zhang, Y. Cui, H. Chen, The effects of vertical farming on indoor carbon dioxide concentration and fresh air energy consumption in office buildings, Building and Environment 195 (2021) 107766.

[86] N. Vivekanandan, K. Rajeswari, N.V. Kanna, A CFD-based assessment of Azolla biofilters for sustainable indoor air purification in low-carbon buildings, International Journal on Interactive Design and Manufacturing (IJIDeM) (2025) 1–14.

[87] T. Pettit, P.J. Irga, F.R. Torpy, The in situ pilot-scale phytoremediation of airborne VOCs and particulate matter with an active green wall, Air Quality, Atmosphere & Health 12 (2019) 33–44.

[88] F. Torpy, M. Zavattaro, Bench-study of green-wall plants for indoor air pollution reduction, Journal of Living Architecture (2018).

[89] D. Tudiwer, A. Korjenic, The effect of an indoor living wall system on humidity, mould spores and CO2-concentration, Energy and Buildings 146 (2017) 73–86.

[90] R. Fleck, R.L. Gill, T. Pettit, P.J. Irga, N.L.R. Williams, J.R. Seymour, F.R. Torpy, Characterisation of fungal and bacterial dynamics in an active green wall used for indoor air pollutant removal, Building and Environment 179 (2020) 106987.

[91] K. Rodgers, R. Handy, W. Hutzel, Indoor air quality (IAQ) improvements using biofiltration in a highly efficient residential home, Journal of Green Building 8 (2013) 22–27.

[92] Y. Liu, B. Considine, A. McNabola, Assessment of hygrothermal performance and mould growth risk in roofs of post-retrofitted non-dormer and dormer attic rooms with reduced ventilation, Building and Environment 250 (2024) 111172.

[93] M. Budaniya, A.K. Mishra, A.C. Rai, M.S. Dasgupta, Indoor plants' effect on occupants' performance, perceived comfort, and affect in an open-plan space in composite climatic regions, India, Building and Environment 274 (2025) 112785.

[94] X. Ma, M. Du, P. Deng, T. Zhou, B. Hong, Effects of green walls on thermal perception and cognitive performance: An indoor study, Building and Environment 250 (2024) 111180.

[95] E. Iddio, L. Wang, H. Zhang, N.H. Wong, The effects of indoor living walls on occupant thermal comfort in office buildings, Science and Technology for the Built Environment 31 (2025) 398–414.

[96] S. Tashiro, Y. Harada, Psychological and physiological thermal effects of biophilic built environment using virtual reality: A pilot study for certified green building, Building and Environment 270 (2025) 112534.

[97] G. Mangone, S.R. Kurvers, P.G. Luscuere, Constructing thermal comfort: Investigating the effect of vegetation on indoor thermal comfort through a four season thermal comfort quasi-experiment, Building and Environment 81 (2014) 410–426.

[98] A. Lipczynska, J. Kaczmarczyk, B. Dziedzic, Effect of Indoor Green Walls on Environment Perception and Well-Being of Occupants in Office Buildings, Energies 17 (2024) 5690.

[99] F. Liu, X. Meng, Integrating the Living Wall with Mechanical Ventilation to Improve Indoor Thermal Environment in the Transition Season, Sustainability 16 (2024) 4300.

[100] N. Ding, F. Liu, F. Pang, J. Su, L. Yan, X. Meng, Integrating the living wall with the split air conditioner towards indoor heating environment improvement in winter, Case Studies in Thermal Engineering 47 (2023) 103061.

[101] L. Wang, L.K. Norford, M. Witte, Modeling Thermal Impacts of Indoor Living Plants in the Built Environment, (2025). https://doi.org/10.2139/ssrn.5191088.

[102] U.K. Priya, R. Senthil, Enhancing sustainable thermal comfort of tropical urban buildings with indoor plants, Buildings 14 (2024) 2353.

[103] H. Al Sayyed, W. Al-Azhari, Investigating the role of biophilic design to enhance comfort in residential spaces: human physiological response in immersive virtual environment, Frontiers in Virtual Reality 6 (2025) 1411425.

[104] S. de Vries, T. Hermans, F. Langers, Effects of indoor plants on office workers: a field study in multiple Dutch organizations, Frontiers in Psychology 14 (2023) 1196106.

[105] L. Morawska, P.K. Thai, X. Liu, A. Asumadu-Sakyi, G. Ayoko, A. Bartonova, A. Bedini, F. Chai, B. Christensen, M. Dunbabin, Applications of low-cost sensing technologies for air quality monitoring and exposure assessment: How far have they gone?, Environment International 116 (2018) 286–299.

[106] F. Carotenuto, A. Bisignano, L. Brilli, G. Gualtieri, L. Giovannini, Low-cost air quality monitoring networks for long-term field campaigns: A review, Meteorological Applications 30 (2023) e2161.

[107] S. Yin, H. Ibrahim, P.S. Schnable, M.J. Castellano, L. Dong, A field-deployable, wearable leaf sensor for continuous monitoring of vapor-pressure deficit, Advanced Materials Technologies 6 (2021) 2001246.

[108] E. Heseltine, J. Rosen, WHO guidelines for indoor air quality: dampness and mould, (2009).

[109] Z. Yang, W. Gao, D. Yang, X. Hu, T. Xu, Impact of Air Velocity on Mold Growth in High Temperature and Humidity Conditions: An Experimental Approach, Buildings 14 (2024) 2145.

[110] Y. Shao, J. Li, Z. Zhou, F. Zhang, Y. Cui, The impact of indoor living wall system on air quality: a comparative monitoring test in building corridors, Sustainability 13 (2021) 7884.

[111] U. Yanagi, N. Fukushima, H. Nagai, H. Ye, M. Kano, Bioaerosol Sensor for In Situ Measurement: Real-Time Measurement of Bioaerosol Particles in a Real Environment and Demonstration of the Effectiveness of Air Purifiers to Reduce Bioaerosol Particle Concentrations at Hot Spots, Atmosphere 14 (2023) 1656.

[112] Y. Qian, J. Leng, K. Zhou, Y. Liu, How to measure and control indoor air quality based on intelligent digital twin platforms: A case study in China, Building and Environment 253 (2024) 111349.

[113] D. Latoń, J. Grela, A. Ożadowicz, L. Wisniewski, Artificial Intelligence and Machine Learning Approaches for Indoor Air Quality Prediction: A Comprehensive Review of Methods and Applications, Energies 18 (2025) 5194.

[114] E. Alotaibi, N. Nassif, Artificial intelligence in environmental monitoring: in-depth analysis, Discover Artificial Intelligence 4 (2024) 84.

[115] C. Boje, A. Guerriero, S. Kubicki, Y. Rezgui, Towards a semantic Construction Digital Twin: Directions for future research, Automation in Construction 114 (2020) 103179.

[116] A.B. Darlington, J.F. Dat, M.A. Dixon, The biofiltration of indoor air: air flux and temperature influences the removal of toluene, ethylbenzene, and xylene, Environmental Science & Technology 35 (2001) 240–246.

[117] X. Hu, R.H. Assaad, A BIM-enabled digital twin framework for real-time indoor environment monitoring and visualization by integrating autonomous robotics, LiDAR-based 3D mobile mapping, IoT sensing, and indoor positioning technologies, Journal of Building Engineering 86 (2024) 108901.

[118] A. Reyes Yanes, R. Abbasi, P. Martinez, R. Ahmad, Digital twinning of hydroponic grow beds in intelligent aquaponic systems, Sensors 22 (2022) 7393.

[119] J.M. Dorick, D. Macarisin, L. Dunn, G.D. Kumar, Effect of aquaponic water and substratum material on biofilm formation by Aeromonas hydrophila, International Journal of Food Microbiology 404 (2023) 110316.

[120] C. Gao, D. Wang, Comparative study of model-based and model-free reinforcement learning control performance in HVAC systems, Journal of Building Engineering 74 (2023) 106852.

[121] C. Sekhar, M. Akimoto, X. Fan, M. Bivolarova, C. Liao, L. Lan, P. Wargocki, Bedroom ventilation: Review of existing evidence and current standards, Building and Environment 184 (2020) 107229.

[122] W. Cho, J. Heo, M.H. Park, H.J. Seo, K. Lee, D.G. Lee, Y. Kim, Energy performance and thermal comfort of integrated energy recovery ventilator system with air-conditioner for passive buildings, Energy and Buildings 295 (2023) 113302.

[123] L.J. Martin, R.I. Adams, A. Bateman, H.M. Bik, J. Hawks, S.M. Hird, D. Hughes, S.W. Kembel, K. Kinney, S.-O. Kolokotronis, Evolution of the indoor biome, Trends in Ecology & Evolution 30 (2015) 223–232.

[124] M.J. Blaser, The theory of disappearing microbiota and the epidemics of chronic diseases, Nature Reviews Immunology 17 (2017) 461–463.

[125] J.M. Robinson, H. Watkins, I. Man, C. Liddicoat, R. Cameron, B. Parker, M. Cruz, L. Meagher, Microbiome-Inspired Green Infrastructure: a bioscience roadmap for urban ecosystem health, Arq: Architectural Research Quarterly 25 (2021) 292–303.

[126] L.T. Stiemsma, L.A. Reynolds, S.E. Turvey, B.B. Finlay, The hygiene hypothesis: current perspectives and future therapies, ImmunoTargets and Therapy (2015) 143–157.

[127] Y. Dockx, M. Täubel, E.M. Bijnens, K. Witters, M. Valkonen, B. Jayaprakash, J. Hogervorst, T.S. Nawrot, L. Casas, Indoor green can modify the indoor dust microbial communities, Indoor Air 32 (2022) e13011.

[128] G. Berg, A. Mahnert, C. Moissl-Eichinger, Beneficial effects of plant-associated microbes on indoor microbiomes and human health?, Frontiers Media SA, 2014.

[129] S.T. Kelley, J.A. Gilbert, Studying the microbiology of the indoor environment, Genome Biology 14 (2013) 202.

[130] L. Veal, United States environmental protection agency, US Environmental Protection Agency (EPA)(2005) National Management Measures to Control Non-Point Source Pollution for Urban Areas (2021).

[131] R.I. Adams, A.C. Bateman, H.M. Bik, J.F. Meadow, Microbiota of the indoor environment: a meta-analysis, Microbiome 3 (2015) 49.

[132] K.C. Dannemiller, J.F. Gent, B.P. Leaderer, J. Peccia, Influence of housing characteristics on bacterial and fungal communities in homes of asthmatic children, Indoor Air 26 (2016) 179–192.

[133] J.R. Thompson, A. Argyraki, M. Bashton, L. Bramwell, M. Crown, A.S. Hursthouse, K. Jabeen, P. Marinho Reis, A. Namdeo, A. Nelson, Bacterial diversity in house dust: characterization of a core indoor microbiome, Frontiers in Environmental Science 9 (2021) 754657.

[134] S.W. Kembel, J.F. Meadow, T.K. O’Connor, G. Mhuireach, D. Northcutt, J. Kline, M. Moriyama, G.Z. Brown, B.J. Bohannan, J.L. Green, Architectural design drives the biogeography of indoor bacterial communities, PloS One 9 (2014) e87093.

[135] P. Kumar, M.A. Kausar, A.B. Singh, R. Singh, Biological contaminants in the indoor air environment and their impacts on human health, Air Quality, Atmosphere & Health 14 (2021) 1723–1736.

[136] K.M. Hewitt, C.P. Gerba, S.L. Maxwell, S.T. Kelley, Office space bacterial abundance and diversity in three metropolitan areas, PloS One 7 (2012) e37849.

[137] H. Urakawa, Y. Tajima, Y. Numata, S. Tsuneda, Low temperature decreases the phylogenetic diversity of ammonia-oxidizing archaea and bacteria in aquarium biofiltration systems, Applied and Environmental Microbiology 74 (2008) 894–900.

[138] M.L. Kakumanu, J.M. Maritz, J.M. Carlton, C. Schal, Overlapping community compositions of gut and fecal microbiomes in lab-reared and field-collected German cockroaches, Applied and Environmental Microbiology 84 (2018) e01037-18.

[139] G.E. Flores, S.T. Bates, D. Knights, C.L. Lauber, J. Stombaugh, R. Knight, N. Fierer, Microbial biogeography of public restroom surfaces, PloS One 6 (2011) e28132.

[140] K.E. Fujimura, C.C. Johnson, D.R. Ownby, M.J. Cox, E.L. Brodie, S.L. Havstad, E.M. Zoratti, K.J. Woodcroft, K.R. Bobbitt, G. Wegienka, Man's best friend? The effect of pet ownership on house dust microbial communities, Journal of Allergy and Clinical Immunology 126 (2010) 410-412. e3.

[141] S.W. Kembel, E. Jones, J. Kline, D. Northcutt, J. Stenson, A.M. Womack, B.J. Bohannan, G.Z. Brown, J.L. Green, Architectural design influences the diversity and structure of the built environment microbiome, The ISME Journal 6 (2012) 1469–1479.

[142] H.A. Burge, W.R. Solomon, M.L. Muilenberg, Evaluation of indoor plantings as allergen exposure sources, Journal of Allergy and Clinical Immunology 70 (1982) 101–108.

[143] M.H. Leung, X. Tong, P.K. Lee, Indoor microbiome and airborne pathogens, Comprehensive Biotechnology (2019) 96.

[144] W.A. Wicaksono, T. Reisenhofer-Graber, S. Erschen, P. Kusstatscher, C. Berg, R. Krause, T. Cernava, G. Berg, Phyllosphere-associated microbiota in built environment: do they have the potential to antagonize human pathogens?, Journal of Advanced Research 43 (2023) 109–121.

[145] I. Laforest-Lapointe, C. Messier, S.W. Kembel, Tree leaf bacterial community structure and diversity differ along a gradient of urban intensity, MSystems 2 (2017) 10.1128/msystems. 00087-17.

[146] K.M. Dastogeer, F.H. Tumpa, A. Sultana, M.A. Akter, A. Chakraborty, Plant microbiome–an account of the factors that shape community composition and diversity, Current Plant Biology 23 (2020) 100161.

[147] J.F. Meadow, A.E. Altrichter, S.W. Kembel, J. Kline, G. Mhuireach, M. Moriyama, D. Northcutt, T.K. O'Connor, A.M. Womack, G.Z. Brown, Indoor airborne bacterial communities are influenced by ventilation, occupancy, and outdoor air source, Indoor Air 24 (2014) 41–48.

[148] G. Mhuireach, B.R. Johnson, A.E. Altrichter, J. Ladau, J.F. Meadow, K.S. Pollard, J.L. Green, Urban greenness influences airborne bacterial community composition, Science of the Total Environment 571 (2016) 680–687.

[149] L. Soininen, M.I. Roslund, N. Nurminen, R. Puhakka, O.H. Laitinen, H. Hyöty, A. Sinkkonen, Indoor green wall affects health-associated commensal skin microbiota and enhances immune regulation: a randomized trial among urban office workers, Scientific Reports 12 (2022) 6518.

[150] A.J. Probst, A.K. Auerbach, C. Moissl-Eichinger, Archaea on human skin, PloS One 8 (2013) e65388.

[151] M.I. Roslund, R. Puhakka, N. Nurminen, S. Oikarinen, N. Siter, M. Grönroos, O. Cinek, L. Kramná, A. Jumpponen, O.H. Laitinen, Long-term biodiversity intervention shapes health-associated commensal microbiota among urban day-care children, Environment International 157 (2021) 106811.

[152] M. Labouyrie, C. Ballabio, F. Romero, P. Panagos, A. Jones, M.W. Schmid, V. Mikryukov, O. Dulya, L. Tedersoo, M. Bahram, Patterns in soil microbial diversity across Europe, Nature Communications 14 (2023) 3311.

[153] N. Baker, K. Steemers, Healthy homes: Designing with light and air for sustainability and wellbeing, Riba Publishing, 2019.

[154] D. Licina, S. Yildirim, Occupant satisfaction with indoor environmental quality, sick building syndrome (SBS) symptoms and self-reported productivity before and after relocation into WELL-certified office buildings, Building and Environment 204 (2021) 108183.

[155] H. Jo, C. Song, Y. Miyazaki, Physiological benefits of viewing nature: A systematic review of indoor experiments, International Journal of Environmental Research and Public Health 16 (2019) 4739.

[156] M. Hanc, C. McAndrew, M. Ucci, Conceptual approaches to wellbeing in buildings: A scoping review, Building Research & Information 47 (2019) 767–783.

[157] T. Hartig, A. Böök, J. Garvill, T. Olsson, T. Gärling, Environmental influences on psychological restoration, Scandinavian Journal of Psychology 37 (1996) 378–393.

[158] R.S. Ulrich, R.F. Simons, B.D. Losito, E. Fiorito, M.A. Miles, M. Zelson, Stress recovery during exposure to natural and urban environments, Journal of Environmental Psychology 11 (1991) 201–230.

[159] S. Kaplan, The restorative benefits of nature: Toward an integrative framework, Journal of Environmental Psychology 15 (1995) 169–182.

[160] R. Kaplan, S. Kaplan, The experience of nature: A psychological perspective, Cambridge university press, 1989.

[161] S. Altomonte, S. Kaçel, P.W. Martinez, D. Licina, What is NExT? A new conceptual model for comfort, satisfaction, health, and well-being in buildings, Building and Environment 252 (2024) 111234.

[162] T. Bringslimark, T. Hartig, G.G. Patil, The psychological benefits of indoor plants: A critical review of the experimental literature, Journal of Environmental Psychology 29 (2009) 422–433.

[163] S.W. Ostner, The benefits of nature in the workplace, A Handbook of Theories on Designing Alignment between People and the Office Environment 169 (2021).

[164] V.I. Lohr, C.H. Pearson-Mims, G.K. Goodwin, Interior plants may improve worker productivity and reduce stress in a windowless environment, Journal of Environmental Horticulture 14 (1996) 97–100.

[165] Q. Lei, C. Yuan, S.S.Y. Lau, A quantitative study for indoor workplace biophilic design to improve health and productivity performance, Journal of Cleaner Production 324 (2021) 129168.

[166] K. Li, A. Perrault, W.A. DeYoung, E. Cameron, C.T. Miller, A.S. O'Connor, M. Gu, B. Braun, Impact of biophilic design on college student perception of mental health and environmental benefits: A dose-response study, Building and Environment 267 (2025) 112318.

[167] N. Hähn, E. Essah, T. Blanusa, Biophilic design and office planting: a case study of effects on perceived health, well-being and performance metrics in the workplace, Intelligent Buildings International 13 (2021) 241–260.

[168] C.I. Nykiforuk, H. Vallianatos, L.M. Nieuwendyk, Photovoice as a method for revealing community perceptions of the built and social environment, International Journal of Qualitative Methods 10 (2011) 103–124.

[169] V. Braun, V. Clarke, Thematic analysis: A practical guide, (2021).

[170] N.K. Gale, G. Heath, E. Cameron, S. Rashid, S. Redwood, Using the framework method for the analysis of qualitative data in multi-disciplinary health research, BMC Medical Research Methodology 13 (2013) 117.

[171] C. Keyworth, T. Epton, J. Goldthorpe, R. Calam, C.J. Armitage, Acceptability, reliability, and validity of a brief measure of capabilities, opportunities, and motivations ("COM-B"), British Journal of Health Psychology 25 (2020) 474–501.

[172] S.L. Cutter, Vulnerability to environmental hazards, in: Hazards Vulnerability and Environmental Justice, Routledge, 2012: pp. 71–82.

[173] M. Kurmanbekova, J. Du, S. Sharples, A Review of Indoor Air Quality in Social Housing Across Low-and Middle-Income Countries, Applied Sciences 15 (2025) 1858.

[174] E.-J. Lee, S.-J. Park, Strategic Biophilic Residential Design Based on Seniors' Health Profiles: A HRQoL-Driven Approach, Buildings 15 (2025) 1792.

[175] C. Smith, A. Drinkwater, M. Modlich, D. Van Der Horst, R. Doherty, IAQ and environmental health literacy: lived experiences of vulnerable people, Buildings & Cities 5 (2024) 231–246.

[176] L. Hasova, C. Robinson, L. Zhang, Indoor air quality vulnerability along the urban-rural continuum: A neighbourhood classification of exposure for England and Wales, Environment and Planning B: Urban Analytics and City Science (2025) 23998083251344678.

[177] R. Shrestha, J. Flacke, J. Martinez, M. Van Maarseveen, Environmental health related socio-spatial inequalities: identifying "hotspots" of environmental burdens and social vulnerability, International Journal of Environmental Research and Public Health 13 (2016) 691.

[178] J.A. Sarnat, S.E. Sarnat, W.D. Flanders, H.H. Chang, J. Mulholland, L. Baxter, V. Isakov, H. Özkaynak, Spatiotemporally resolved air exchange rate as a modifier of acute air pollution-related morbidity in Atlanta, Journal of Exposure Science & Environmental Epidemiology 23 (2013) 606–615.

[179] R. Kumar, V. Verma, M. Thakur, G. Singh, B. Bhargava, A systematic review on mitigation of common indoor air pollutants using plant-based methods: a phytoremediation approach, Air Quality, Atmosphere & Health 16 (2023) 1501–1527.

[180] J. Yang, J. Duan, X. Niu, T. Hu, Y. Huang, J. Sun, J. Cao, A comprehensive review on indoor air pollutants and their health impacts: priority pollutants and suggested mitigations, Air Quality, Atmosphere & Health (2025) 1–34.

[181] K. Halbmayer, J. Hollands, S. Alasu, A. Korjenic, B. Pichler, E. Reitinger, E. Zojer, B. Knoll, A. Renkin, R. Dopheide, GREEN: Cool & Care—Research and Development of Greening Measures in Nursing Homes in Austria. Technical and Social Interconnections, Sustainability 13 (2021) 11469.

[182] M. Tomkins, S. Yousef, A. Adam-Bradford, C. Perkins, E. Grosrenaud, M. Mctough, A. Viljoen, Cultivating refuge: The role of urban agriculture amongst refugees and forced migrants in the Kurdistan region of Iraq, Urban Agriculture and City Sustainability 131 (2019).

[183] H. Rasheed, T.K. Jayasree, The multifaceted role of indoor plants: A comprehensive review of their impact on air quality, health, and perception, Energy and Buildings (2025) 115312.[184] C. Gubb, T. Blanusa, A. Griffiths, C. Pfrang, Can plants be considered a building service?, Building Services Engineering Research and Technology 41 (2020) 374–384.

[185] A.A. Alvarado-Alvarado, W. Smets, P. Irga, S. Denys, Engineering green wall botanical biofiltration to abate indoor volatile organic compounds: A review on mechanisms, phyllosphere bioaugmentation, and modeling, Journal of Hazardous Materials 465 (2024) 133491.

[186] M.S. Montaluisa-Mantilla, P. García-Encina, R. Lebrero, R. Muñoz, Botanical filters for the abatement of indoor air pollutants, Chemosphere 345 (2023) 140483.

[187] J.A. Russell, Y. Hu, L. Chau, M. Pauliushchyk, I. Anastopoulos, S. Anandan, M.S. Waring, Indoor-biofilter growth and exposure to airborne chemicals drive similar changes in plant root bacterial communities, Applied and Environmental Microbiology 80 (2014) 4805–4813.

[188] S. Oh, C. Lu, Vertical farming-smart urban agriculture for enhancing resilience and sustainability in food security, The Journal of Horticultural Science and Biotechnology 98 (2023) 133–140.

[189] P. Julinova, D. Beckovsky, Perspectives of moss species in urban ecosystems and vertical living-architecture: A review, Advances in Engineering Materials, Structures and Systems: Innovations, Mechanics and Applications (2019) 2370–2375.

[190] S. Kaur, S.K. Mishra, V. Goel, M. Kumar, R. Singh, M. Devi, H. Chandra, V. Narayanasamy, S.P. Singh, P. Sharma, Impact of indoor plant-induced relative humidity on PM concentration in indoor urban environment, Atmospheric Pollution Research 16 (2025) 102468.

[191] S. Sharma, A. Bakht, M. Jahanzaib, H. Lee, D. Park, Evaluation of the effectiveness of common indoor plants in improving the indoor air quality of studio apartments, Atmosphere 13 (2022) 1863.

[192] N. Al Qassimi, C. Jung, Impact of air-purifying plants on the reduction of volatile organic compounds in the indoor hot desert climate, Frontiers in Built Environment 7 (2022) 803516.

[193] N.M. Jamaludin, N. Mahyuddin, F.W. Akashah, Assessment on Indoor Environmental Quality (IEQ) with the application of potted plants in the classroom: case of University Malaya, Journal of Design and Built Environment 17 (2017) 1–15.

[194] A. Campiotti, E. Ricciardi, G. Spano, L. Dominici, E. Comino, R. Riggio, F. Pitasi, L. Ribotta, S. Barbero, G. Sanesi, Indoor green walls for improving air quality and human well-being: a case study from a primary school in Turin (Italy), Nature-Based Solutions (2025) 100280.

[195] B.D. Vanicela, M. Nebel, M. Stephan, C. Riethmüller, G.T. Gresser, Quantitative analysis of fine dust particles on moss surfaces under laboratory conditions using the example of Brachythecium rutabulum, Environmental Science and Pollution Research 28 (2021) 51763–51771.

[196] H.S. Smith, P.J. Irga, R. Fleck, F.R. Torpy, Portable botanical biofilters to address internal combustion engine exhaust exposure, Building and Environment 244 (2023) 110777.

[197] F. Ahmed, S.M.H. Rahman, Thermal performance of green balconies of residential buildings: A Case Study in Wari, Dhaka, (2024).

[198] B. Riley, The state of the art of living walls: Lessons learned, Building and Environment 114 (2017) 219–232.

[199] M. Frontczak, P. Wargocki, Literature survey on how different factors influence human comfort in indoor environments, Building and Environment 46 (2011) 922–937.

[200] M. Manso, J. Castro-Gomes, Green wall systems: A review of their characteristics, Renewable and Sustainable Energy Reviews 41 (2015) 863–871.

[201] H. Wang, C. Lei, A numerical investigation of combined solar chimney and water wall for building ventilation and thermal comfort, Building and Environment 171 (2020) 106616.

[202] G. Pérez, J. Coma, S. Sol, L.F. Cabeza, Green facade for energy savings in buildings: The influence of leaf area index and facade orientation on the shadow effect, Applied Energy 187 (2017) 424–437.

[203] T.A. Moya, A. van den Dobbelsteen, M. Ottele, P.M. Bluyssen, Green air conditioning: Using indoor living wall systems as a climate control method, Rehva Journal (2017) 27–31.

[204] F. Ascione, R.F. De Masi, M. Mastellone, S. Ruggiero, G.P. Vanoli, Green walls, a critical review: Knowledge gaps, design parameters, thermal performances and multi-criteria design approaches, Energies 13 (2020) 2296.

[205] M. Goel, B. Jha, S. Khan, Living walls enhancing the urban realm: a review, Environmental Science and Pollution Research 29 (2022) 38715–38734.

[206] A. Biswal, H. Sun, I. Bray, O. Cranshaw, T.R. Kjeldsen, C.C. Pain, T. Roberts, D. Sinnett, T. Wild, J. Wenk, Household driven and council managed street greening: scoring cost, expertise, space, and cost-benefits of green infrastructure combinations, Sustainable Horizons 17 (2025).

[207] O. Gocer, A. Ramezannia, C. Allison, The practical challenges of living wall implementations in Australia, Intelligent Buildings International (2025) 1–14.

[208] B. Kotzen, E.R. Galea, S. Mosco, Z. Wang, J. Ewer, F. Jia, Fire safety risks of external living walls and implications for regulatory guidance in England, Fire Safety Journal 139 (2023) 103816.

[209] Y. Nasr, H. El Zakhem, A.E.A. Hamami, M. El Bachawati, R. Belarbi, Comprehensive assessment of the impact of green roofs and walls on building energy performance: a scientific review, Energies 17 (2024) 5160.

List of Tables

Table 1. Summary of the most relevant ten-question and related reviews on indoor green infrastructure, indoor environmental quality and associated topics, listed in descending order of publication year.

References	Focus area	What was covered / Key findings
Ten questions papers		
Aslanoğlu et al. [16]	The paper explores how urban greenery can shape sustainable, resilient, and inclusive future cities.	It addresses ten questions on ecosystem services, climate adaptation, carbon reduction, spatial development, technology, social and health benefits, risks, global case studies, and future governance, highlighting both opportunities and challenges of urban greenery.
Schweiker et al. [17]	Explores how subjective rating scales are used to assess IEQ and the challenges in their reliability, variation, and interpretation.	Addresses ten questions on the history, language, variations, biases, alternatives, and future improvements of scales, emphasising the need for fit-for-purpose approaches to advance IEQ research.
Booker et al. [18]	Investigates future challenges for residential IAQ and environmental justice.	Explores impacts of climate, policy, demographics, and behaviours on IAQ, highlighting inequities and the role of transdisciplinary research in achieving just solutions.
Nazaroff [19]	Reviews the sources, dynamics, and health risks of ultrafine particles indoors.	Addresses outdoor infiltration, indoor generation, building factors, dynamic processes, and mitigation strategies, highlighting health risks and control opportunities.
Awada et al. [20]	Assesses how office environments contribute to stress and recovery.	Discusses environmental conditions, design features, stress pathways, and recovery strategies, pointing to opportunities for healthier workplace design.
Taylor et al. [21]	Analyses causes, risks, and responses to overheating in dwellings under climate change	Covers definitions, measurements, impacts, vulnerabilities, adaptation strategies, and policy needs, emphasising coordinated action for thermal comfort and energy efficiency.
Ghaddar & Ghali [22]	Examines strategies to mitigate infectious aerosol transmission in hot and humid climates with minimal energy cost.	Reviews macro- and microenvironmental approaches (ventilation, filtering, localised control), addressing technological trade-offs and sustainable solutions.

Steinemann [23]	Explores the role and impact of fragrance-free policies in indoor settings.	Examines motivations, implementations, benefits, and challenges of such policies, emphasising their potential to reduce IAQ-related health issues.
Hoisington et al. [24]	Examines how indoor environments influence mental health outcomes.	Covers pathways via air quality, microbiomes, and environmental exposures, suggesting mechanisms and research needs for healthier environments.
Prussin et al. [25]	Reviews how Legionella bacteria spread via aerosols in buildings.	Addresses sources, transmission pathways, epidemiology, engineering controls, and research gaps, emphasising risks and prevention strategies.
Steinemann et al. [26]	Examines how green buildings, while aiming for energy efficiency and sustainability, address (or fail to address) IAQ and occupant health.	It addresses ten questions on definitions of green buildings and IAQ, certification schemes, comparative IAQ performance, risks from green practices and products, climate change implications, immediate and long-term improvement strategies, and research gaps, highlighting that green buildings do not automatically guarantee good indoor air quality.
Hong et al. [27]	Examines the role of occupant behaviour in shaping building energy performance and comfort.	Covers concepts, applications, methodologies, and modelling approaches, highlighting gaps and opportunities to integrate qualitative and quantitative methods for reducing performance gaps.
Adams et al. [28]	Explores the role of building microbiomes in indoor environments and human health.	Covers microbial sources, distributions, human influence, methodological advances, and future directions, highlighting the complexity and importance of indoor microbiomes.
Other related review papers		
Paniccia et al. [29]	Reviews how outdoor and indoor green spaces affect human health and ecosystems under climate change and urbanisation.	Green space exposure enhances mental and physical health while providing ecosystem services, supporting its integration into public health policy and urban planning.
Matheson et al. [30]	Reviews advances in using plants for indoor phytoremediation to improve air quality.	Indoor phytoremediation systems (potted plants, active biofilters, green walls) effectively remove VOCs and other pollutants, but real-world and mixed-pollutant studies remain limited, highlighting the need for field applications, microbial interaction research, and integration with sustainable building design.

Zhao et al. [31]	Reviews epidemiological studies on the association between indoor plants and mental health outcomes.	Limited but consistent evidence suggests indoor plants are linked to reduced stress, depression, and negative emotions, though studies are few, mostly cross-sectional, and concentrated during COVID-19, highlighting the need for more rigorous research.
Fonseca et al. [32]	Explores the health and well-being benefits of outdoor and indoor vertical greening systems (VGSs) in urban environments.	VGSs can improve air quality, thermal comfort, and noise reduction with potential positive impacts on health and well-being, but current evidence is limited and often unquantified, highlighting research gaps in indoor applications, physiological measures, seasonal effects, and cost analysis.
Ravindra & Mor [33]	Reviews the potential of indoor plants for phytoremediation of air pollutants and improving indoor air quality.	Indoor plants can significantly reduce VOCs and other air pollutants through leaves, roots, and microbial interactions, offering a cost-effective way to improve health and comfort, though standardised evaluation, plant selection, and field-based studies are still lacking.
Han et al. [34]	Systematically reviews and meta-analyses the effects of indoor plants on human physiological, cognitive, health-related, and behavioural functions.	Indoor plants positively influence relaxation and cognition, with meta-analysis indicating significant reductions in diastolic blood pressure and improvements in academic performance; however, the strength of evidence varies across outcomes, with some effects supported by limited or heterogeneous studies.
Samudro et al. [35]	Reviews the role of indoor plants as a “phytoarchitecture” platform for building health, emphasising plant-human-environment interactions.	Indoor plants improve air quality, reduce pollutants, and enhance health and wellbeing in schools, workplaces, and homes, supporting their integration into building design through the concept of phytoarchitecture, though attention is needed to avoid harmful species.
Liu et al. [36]	Examines how indoor green plants influence thermal conditions, air quality, and psychological wellbeing in indoor environments.	Indoor plants regulate humidity and temperature, reduce VOCs and CO_2, and enhance learning, work efficiency, and patient recovery, though future research is needed on plant, heating, ventilation and air-conditioning (HVAC) systems integration, pollutant-specific efficiency, and physiological mechanisms.

Samudro & Mangkoedihardjo [37]	Outlines the application principles of indoor phytoremediation using decorative plants to improve air quality.	Indoor plants, especially with diverse species and active root-microbe interactions, can effectively remove VOCs such as formaldehyde and benzene, with efficiency influenced by plant type, plant parts, and environmental conditions, underscoring the importance of biodiversity in sustaining healthy indoor environments.
Persiani [38]	Identifies inconsistencies and research gaps in studies on the benefits of using plants in indoor environments, with attention to plant-related parameters.	Analysis of 31 experimental studies shows major gaps in reporting plant species, health, and environmental conditions, revealing a strong human-centred bias; future research should treat indoor plants as part of an ecological system to improve reliability and design.
Bandehali et al. [39]	Examines the current state of indoor air phytoremediation using potted plants and green walls, focusing on pollutant removal mechanisms, plant species, and applications.	Potted plants and green walls effectively remove VOCs, formaldehyde, benzene, and particulates, also improving thermal comfort and reducing stress, though challenges remain in long-term stability of removal efficiency, pollutant-specific mechanisms, and the role of plant–microbe interactions in sustaining performance.
Han & Ruan [40]	Systematically synthesises quantitative studies on how indoor plants affect air quality and microclimate.	Indoor plants significantly reduce pollutants such as formaldehyde, benzene, and toluene, while also increasing humidity and lowering temperature; plant diversity enhances overall effectiveness, though most evidence comes from short-term lab studies.
Aydogan & Cerone [41]	Summarises evidence on how indoor plants affect air quality, wellbeing, and cognitive performance in built environments.	Indoor plants and their root-microbe systems can remove pollutants such as VOCs while providing psychological, physiological, and cognitive benefits, but most studies rely on sealed chamber experiments with unrealistically high plant densities, highlighting the need for real-world investigations.
Deng & Deng [42]	Summarises the fundamental roles of indoor plants in human health and comfort through photosynthesis, transpiration, psychological effects, and air purification.	Indoor plants release oxygen and negative ions, regulate humidity and temperature, alleviate stress and anxiety, improve productivity, and remove pollutants such as formaldehyde, benzene, and toluene, positioning them as low-cost, sustainable biofilters for healthier indoor environments.

Moya et al. [10]	Provides an overview of indoor green systems (e.g., plants, living walls, biofilters) and their impacts on IEQ.	Green systems can improve IAQ by removing VOCs, regulating temperature and humidity, reducing noise, and enhancing wellbeing and productivity, though real-world evidence is limited and further research is needed on pollutant-removal mechanisms and integration with HVAC systems.
Raji, et al. [43]	Reviews the effects of diverse greening systems (green roofs, vertical greenery, balconies, sky gardens, indoor gardens) on building energy performance across climates.	Greening systems reduce cooling and heating loads through shading, insulation, and evapotranspiration, improve IAQ and comfort, and in some cases lower VOCs and CO_2, but their efficiency varies by climate, system type, and design, requiring further optimisation and cost-benefit analysis.

Table 2. Summary of studies investigating light and water availability impacts on indoor plants' stomatal responses and capacity to remove gaseous pollutants.

References	Plant species	Setting / Context	Light source/ intensity	Key outcomes
Pennisi and van Iersel, [66]	16 different taxa, representing a range of leaf characteristics	Controlled environment (CE), individual potted plants (x6) in bark substrate	CE metal halide and high-pressure sodium lamps 10, 20, 30 micromol m^{-2} s^{-1}	Understanding of indoor light levels' impacts on plant photosynthesis and growth of a very wide range of species
Irga et al., [75]	*Syngonium podophyllum*	CE, individual potted plants (x8) in bark substrate or hydroponics	20 micromol m^{-2} s^{-1}	Understanding of the contribution of rootzone water content on removal of CO_2 and VOCs
Torpy et al., [64]	8 widely used taxa in indoor landscaping	CE, individual potted plants (x8) in bark substrate	10-350 micromol m^{-2} s^{-1} to represent indoor to outdoor range	Leaf-based light response curves and compensation points Whole-potted-plant CO_2 fluxes
Gubb et al., [44]	*Spathiphyllum wallisii* 'Verdi', *Dracaena fragrans* 'Golden Coast' *Zamioculcas zamiifolia*	Individual potted plants in perspex chambers	Dark and 500 lux (20 micromol m^{-2} s^{-1})	Removal of NO_2 in wet and dry soil and light/dark conditions
Berger et al., [62]	5 different taxa, representing a range of leaf/canopy characteristics and transpiration rates, with greater room scale focus on: *Ficus benjamina* *Epipremnum aureum*	Individual potted plants In CE chambers with varying humidity/temperature/VPD 6-12 plants in unoccupied offices in winter, spring and summer	20 micromol m^{-2} s^{-1} Room conditions with supplementary spot-lighting (iro 20-30 micromol m^{-2} s^{-1})	Understanding of the impact of ambient conditions on plants' capacity to humidify air in CE and at room scale in 24 h intervals - species differences in CE but minimal/no impact at office scale

Jiang et al. [69]	*Nephrolepis exaltata*	Room-level humidity changes when different numbers of individual potted plants (0, 5, 18) were employed in unoccupied offices (spring)	Room conditions	Increase in room-scale RH with any plant presence, but no effect on CO_2
Lyu et al., [74]	Active green walls (species monoculture, for 7 different species, x3)	In perspex chambers	Room conditions	Impact of irrigation volumes and flow rates on the efficiency of active system

Table 3. Summary of studies on indoor greening effects on thermal sensation and comfort.

References	Indoor greening intervention	Setting / Context	Thermal metrics assessed	Sample / Duration	Key outcomes	Notes / Limitations
Budaniya et al., [93]	Potted plants (Epipremnum, Dypsis)	AC classroom, composite climate, India	Air temp, RH, CO_2, TSV	118 students; 20 days	Felt cooler (−0.42 TSV); less dryness; stable satisfaction	Young sample; short exposure; energy modelled only
Tashiro & Harada, [96]	VR biophilic office	Two chambers, Tokyo; 24/30 °C	TSV, comfort, HR, HRV, sAA	45 students; ~10 min	Biophilic VR felt cooler; comfort higher	Short VR sessions; student sample; energy estimated
Iddio et al., [95]	Hydroponic living wall, LFAR 25%	Windowless room, ASHRAE 6B, 23-27 °C	Air temp, RH, TSV, TCV, TPV (+PMV comparison)	74 students; ~1 h paired	TSV lower by 0.70 at 24.5 °C; comfort higher	Single room; uncontrolled humidity; energy modelled only
Liu et al., [82]	Active plant wall (hydroponic)	Sealed labs, Qingdao; 3 seasons	Air temp, RH, CO_2,air speed, skin temp	~60 per season; ~40 min	Temp reduction 1 °C; RH higher; comfort near neutral	Lab only; student sample; sealed chamber; short exposure
Wang et al., [101]	Modelled indoor living walls	EnergyPlus simulations	Temp, RH, loads, setpoints	Simulation study; lab data cited	Cooling setpoint raised 0.5-0.9 °C; latent loads increased	Simulation only; latent loads increase; reduced net savings
Al Sayyed & Al-Azhari, [103]	VR biophilic room	VR residential sim, Jordan	SCL, BP	94 adults; ~30 min	Biophilic VR reduced SCL; better recovery and comfort	VR only; no direct TSV votes; short exposure
Ma et al., [94]	Indoor green wall, GVI 0-15%	AC lab, Xi'an, 26 °C	TSV, TCV, BP, HR, EEG	144 students; ~35 min	TSV same; TCV higher with larger wall; improved relaxation	Short exposure; student sample; no energy analysis
Jiang et al., [69]	0, 5, 18 Boston ferns	Three offices, Canberra	RH, temp, CO_2	Six periods; 2 days each	RH increased with plants; temperature unchanged; no comfort votes	No occupants; AC off; one species; short duration

Lipczyńska et al., [98]	Green walls (Epipremnum, Philodendron)	Five Warsaw offices; 3 stages	Temp, RH, thermal/humidity votes	85 staff; ≥2 weeks/stage	Thermal acceptability highest with green walls	HVAC mixing confounding influence; unbalanced survey data
Priya & Senthil, [102]	Potted balcony plants (mixed species)	3-story apartment, Chennai	Indoor/outdoor temp, surface temp, RH	~25 days; 3 phases	Indoor temp lower by up to 2.3 °C	One balcony; short duration; no comfort votes
Berger et al., [62]	Potted Ficus (6)/Epipremnum (12) in a room + chamber ET tests	UK offices; seasonal tests	Humidity, temp, ET	~6 days/season; 24 h periods	Indoor humidity higher in chambers, but not office scale; no temp effect	No comfort votes; unoccupied office; small-scale; short duration
Liu & Meng, [99]	Living wall with ventilation	Two sealed labs, Qingdao	Temp, RH, CO_2, MST, comfort votes	60 students; 80 min	Temp lower; RH higher; comfort scores improved	Short-term; sealed rooms; young sample; single plant species
Ding et al., [100]	Living wall with split AC	Two 3×3×2.8 m rooms, Qingdao	Air temp, air speed, RH, CO_2, TSV, MST	72 students; 80 min	RH higher; TSV shifted from warm to slightly warm; MST lower	Short-term; sealed rooms; student sample; hygiene risks
de Vries et al., [104]	Professionally installed potted plants	Nine Dutch organisations	Dryness, thermal discomfort	594 staff; up to 4 months	Fewer dryness complaints; no change to hot/cold	Quasi-experiment;unbalanced data; seasonality; COVID disruption
Mangone et al., [97]	Potted plants (23-30 per room)	Office, Netherlands; 4 rooms, 4 seasons	Operative temp, RH, TCV, TPV	67 workers; 4 weeks/season (winter 6 weeks)	Comfort +8-12%; ~1.8-1.95× more likely comfortable	Single site; modest sample; mainly psychological

Acronyms: CO_2 = Carbon dioxide; EEG = Electroencephalogram; ET = Evapotranspiration; GVI = Green View Index; HR = Heart rate; HRV = Heart rate variability; LFAR = Leaf-to-floor area ratio; MST = Mean skin temperature; RH = Relative humidity; sAA = Salivary alpha-amylase; SCL = Skin conductance level; SET* = Standard Effective Temperature; TCV = Thermal comfort vote; TPV = Thermal preference vote; TSV = Thermal sensation vote; VR = Virtual reality.

1787 **Tables 4.** Summary of field experimental studies on the effect of indoor greening on IEQ.

References	iGI types	Purpose	Setting	Sample/ Duration	Key outcomes	Plant Species (percentage/ number of plants)	Notes / Limitations
Passive Planting							
Kaur et al. [190]	Floor-integrated potted Plants	IAQ improvements and humidity regulation	Controlled condition (office room)	1 office	Reduction of PM and I/O ratio of PM; increase indoor humidity	Epipremnum aureum (8 pots)	Exposure duration unclear
Sharma et al. [191]	Potted Plants	IAQ improvements	Residential (mechanically ventilated)	4 studio apartments; 2 months	Reduction in CO_2, TVOCs and PM	Sansevieria kirkii, Sansevieria trifasciata, Monstera deliciosa, Zamiifolia and Portulacaria afra	Small sample and single season/location; ventilation behaviour constrained by cold weather
Al Qassimi and Jung [192]	Floor-integrated potted Plants	IAQ improvements	Laboratory rooms (hot desert climate)	2 laboratory rooms; 12 months	Reduction of VOCs; a large planting volume is required	Pachira aquatica, Ficus benjamina, and Aglaonema commutatum	Limited post-installation observation windows and plant set
Jamaludin et al. [193]	Small-scale potted Plants	IAQ improvements and humidity regulation	Classroom (university)	~20–30 occupants; 1 month	Reduction in CO_2 and TVOCs; lowered relative humidity	Peace lily and Janet craig	Single room; short monitoring period; limited participant sample
Vertical Greenery							

Campiotti et al. [194]	Green walls	IAQ improvements	School	Primary school corridor; ~ 18 months	High PM removal, low VOC removal	Marantha leuconera (56), Chamaedorea elegans (104), Pilea peperomioides (65), Chlorophytum comosus (97), Calathea amabilis (86), Calathea ornata (12) and Calathea orbifolia (12).	Single school and installation configuration
Lipczynska et al. [98]	Green walls	IAQ and well-being improvements, thermal conditions regulation	Office	15 offices; 85 occupants; 6 weeks	Improve thermal comfort, perception of air quality and humidity, and working performance (well-being)	Epipremnum aureum and Philodendron scandens	Non-standardised office layout, window orientation and HVAC settings; self-reported well-being and productivity levels
Vanicela et al. [195]	Moss	IAQ improvements	Laboratory	NA	Reduction in fine PM particles	B. rutabulum	Sample size and exposure duration unclear

Pettit et al. [87]	Passive and active green wall	IAQ improvements	Residential and classroom	NA	Reduction in TVOCs and PM; active green wall maintained lower TVOCs.	Passive: Ficus lyrata (1), Schefflera arboricola (1), and Philodendron tatei (1) Active: Chamaedorea elegans (6%), Epipremnum aureum (34%), Ficus lyrata (4%), Neomarica gracillis (5%), Peperomia obtusifolia (10%), Spathiphyllum wallisii (21%) and Syngonium podophyllum (19%).	Sample size and exposure duration unclear
Hydroponic System							
Shao et al. [85]	Vertical farming	IAQ improvements	Office	Office-based modelling	CO_2 reduction	NA	Sample size and exposure duration unclear
Aquatic systems							
NA							
Hybrid Interventions							
Liu and Meng [99]	Living green wall	Temperature and humidity regulation	Controlled condition (laboratory)	Office-based modelling	Reduce indoor temperature and increase relative humidity	Epipremnum aureum	Laboratory setting; sample size and exposure duration unclear

Smith et al. [196]	Botanical biofilters	IAQ improvements	Chamber	2 south-facing laboratories	Reduction in TVOCs and PM; insufficient CO_2 removal rates	Peperomia obtusifolia, Gibasis pellucida, Spathiphyllum wallisii, Peperomia obtusifolia and Nematanthus glabra	Controlled experiment; VOC emissions of iGI
Space-scale Planting							
Ahmed and Rahman [197]	Balcony planters (semi-indoor)	Temperature regulation	Residential	High-rise building	Lowered indoor air and contributed to energy efficiency/saving	NA	Single location; climate/season dependent; exposure duration unclear
Priya and Senthil [102]	Balcony planters (semi-indoor)	Temperature regulation	Residential	Three-storey building; Second floor and north-facing balcony	Lowered indoor air and surface temperatures	Aglaonema modestum, Syngonium angustatum, Dracaena trifasciata, Monstera delisiosa, Philodendron erubescens, Dracaena fragrans, Epipremnum aureum, and Tradescantia spathace	Single balcony/building; exposure duration unclears; shading and resident behaviour

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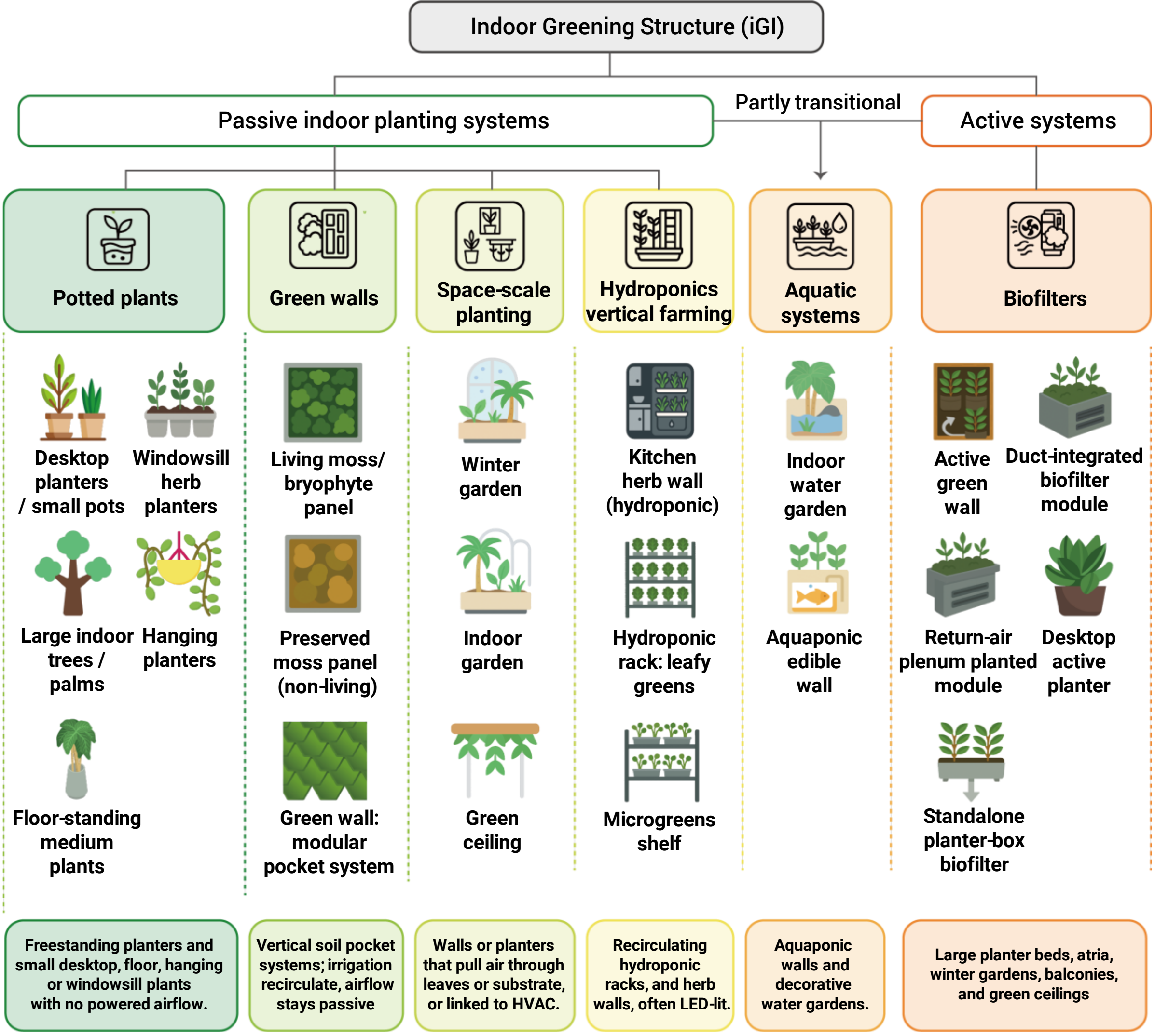


Figure 1. Classification of iGI types into passive, transitional, and active categories (Source: authors' original illustration).

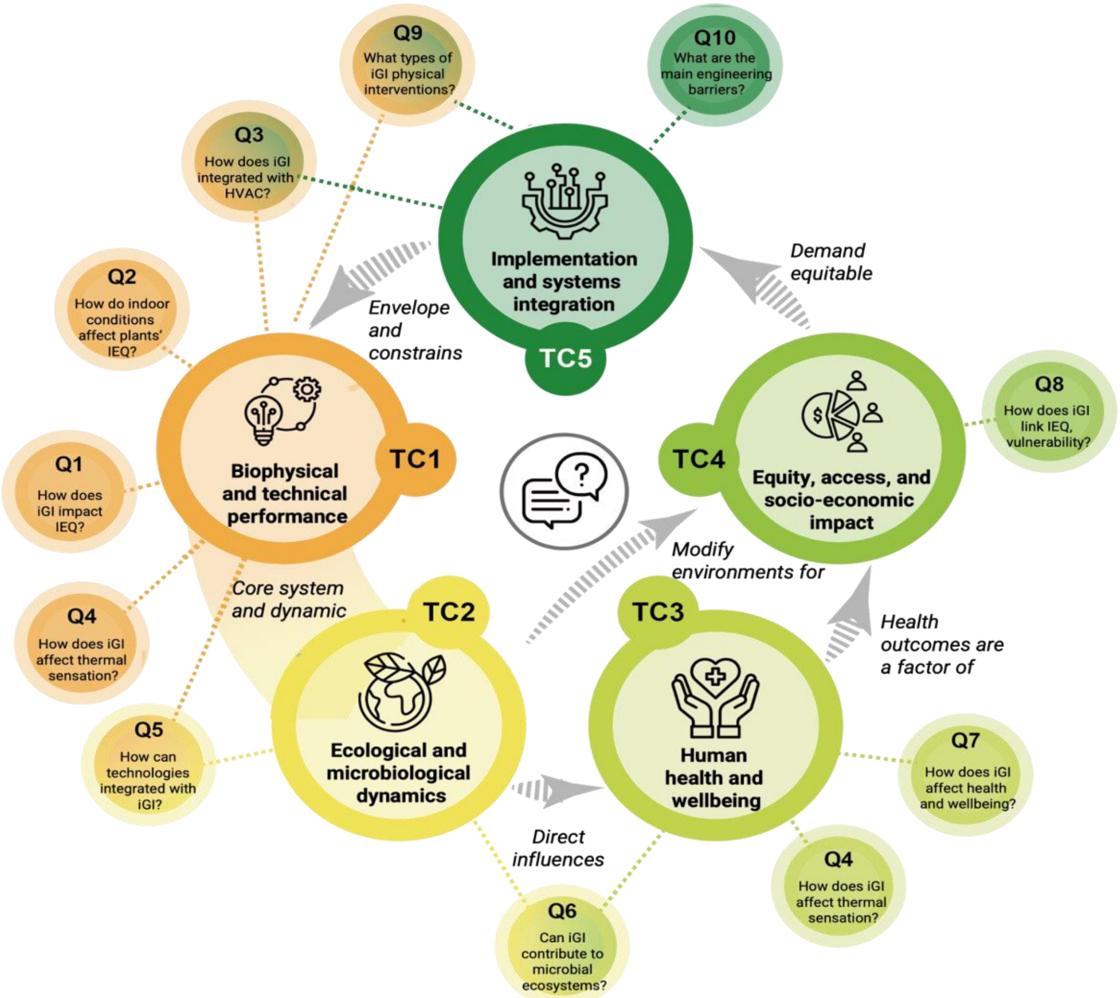


Figure 2. Core-to-Impact conceptual framework depicting the relationships and thematic interlinkages (TC) between the ten research questions (Q). Questions Q3, Q5, Q6, Q9 and Q10 are cross-cutting and associated with more than one thematic cluster (Source: authors' original illustration).

Figure 3. Pathways of iGI influencing IEQ, including effects on pollutants, microclimate, temperature, humidity, noise, stress, and microbial communities (Source: authors' original illustration).

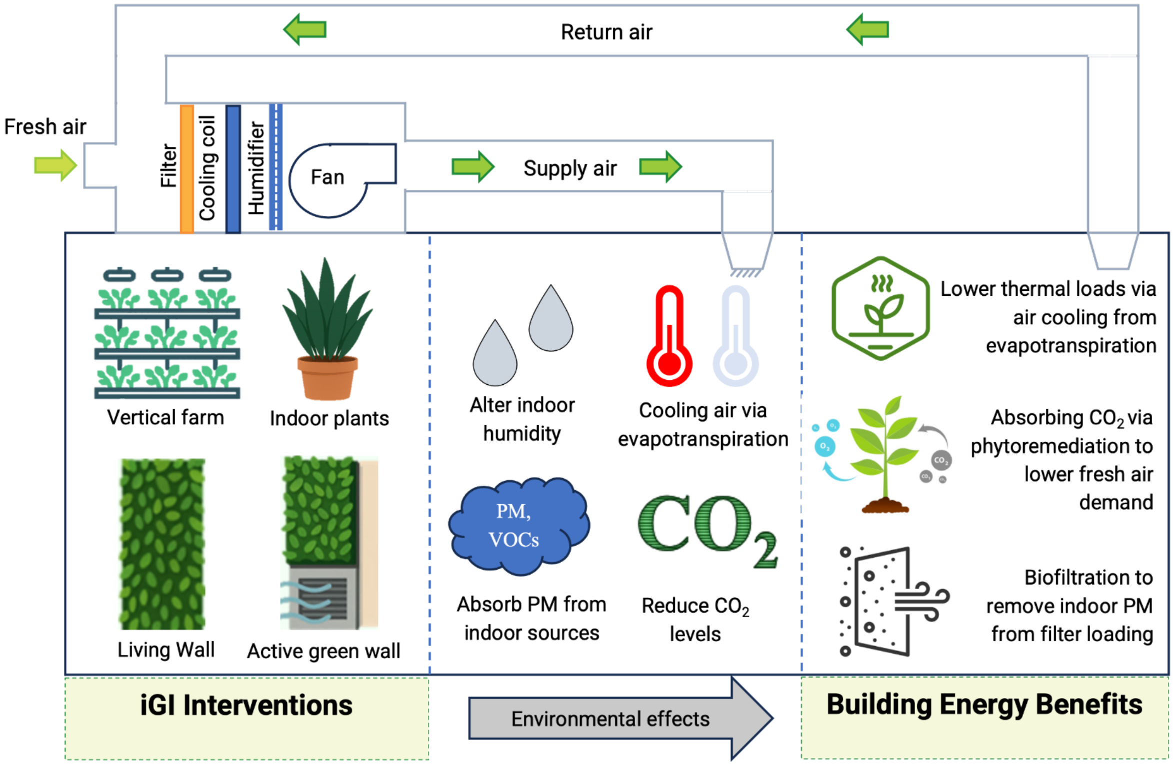


Figure 4. Schematic showing how iGI affects HVAC system performance (Source: authors' original illustration).

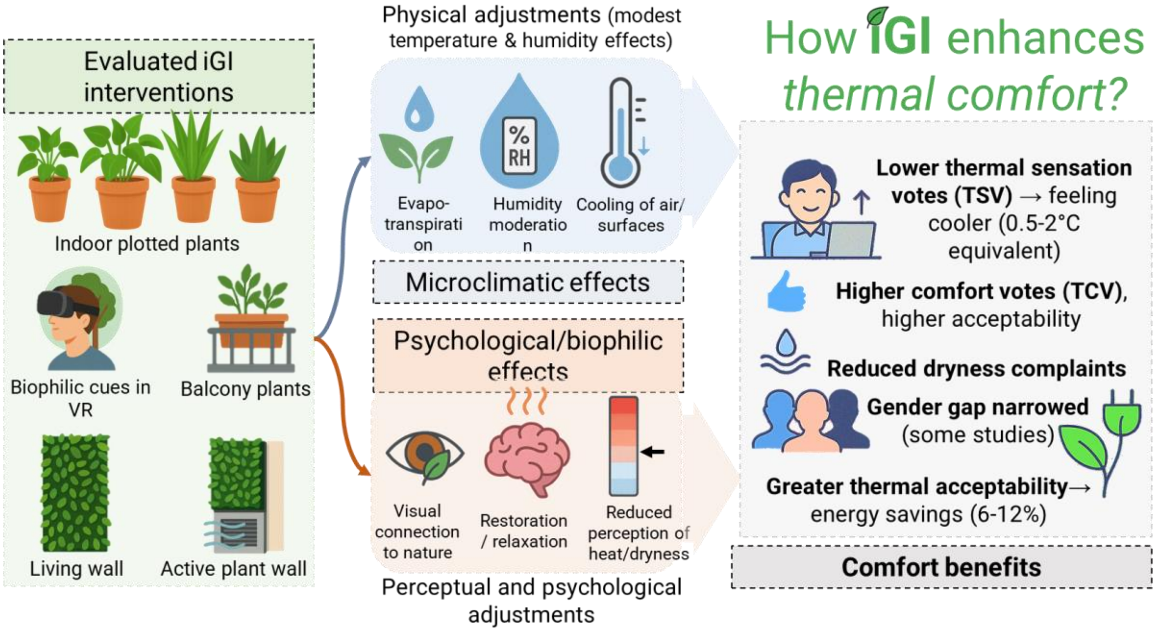


Figure 5. Schematic showing how iGI enhances thermal sensation and comfort (Source: authors' original illustration).

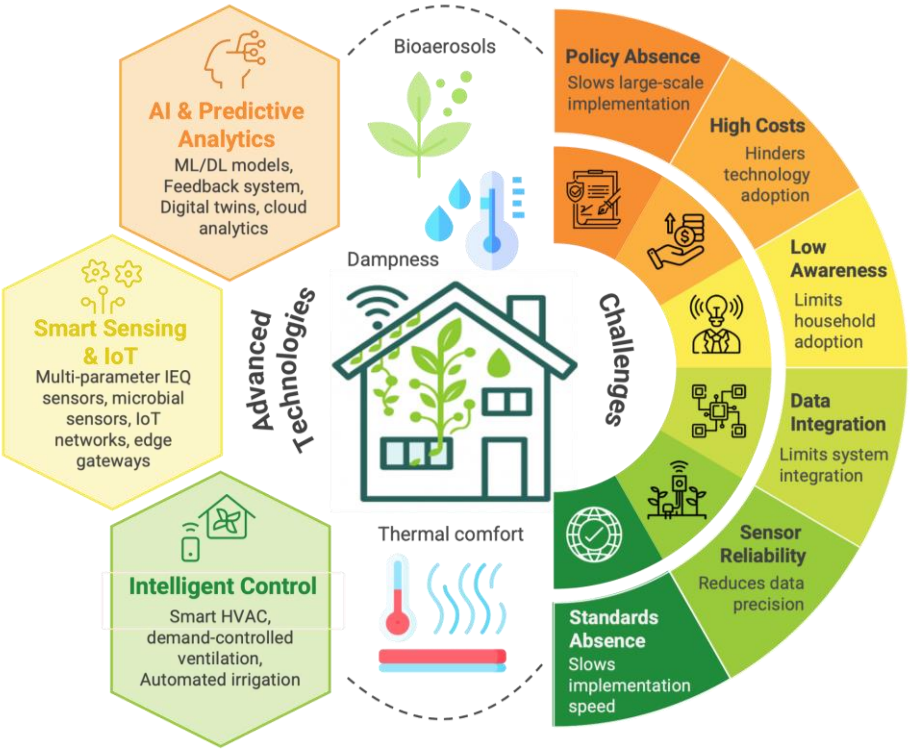


Figure 6. Conceptual illustration of advanced technologies and associated challenges in iGI systems. The framework demonstrates how smart sensing and IoT, AI-driven predictive analytics, and intelligent control form an integrated feedback loop to predict and maintain IEQ, targeting bioaerosol reduction and dampness control. The surrounding wheel highlights key challenges to large-scale adoption, which constrain the real-world scalability of intelligent, self-regulating iGI systems (Source: authors' original illustration).

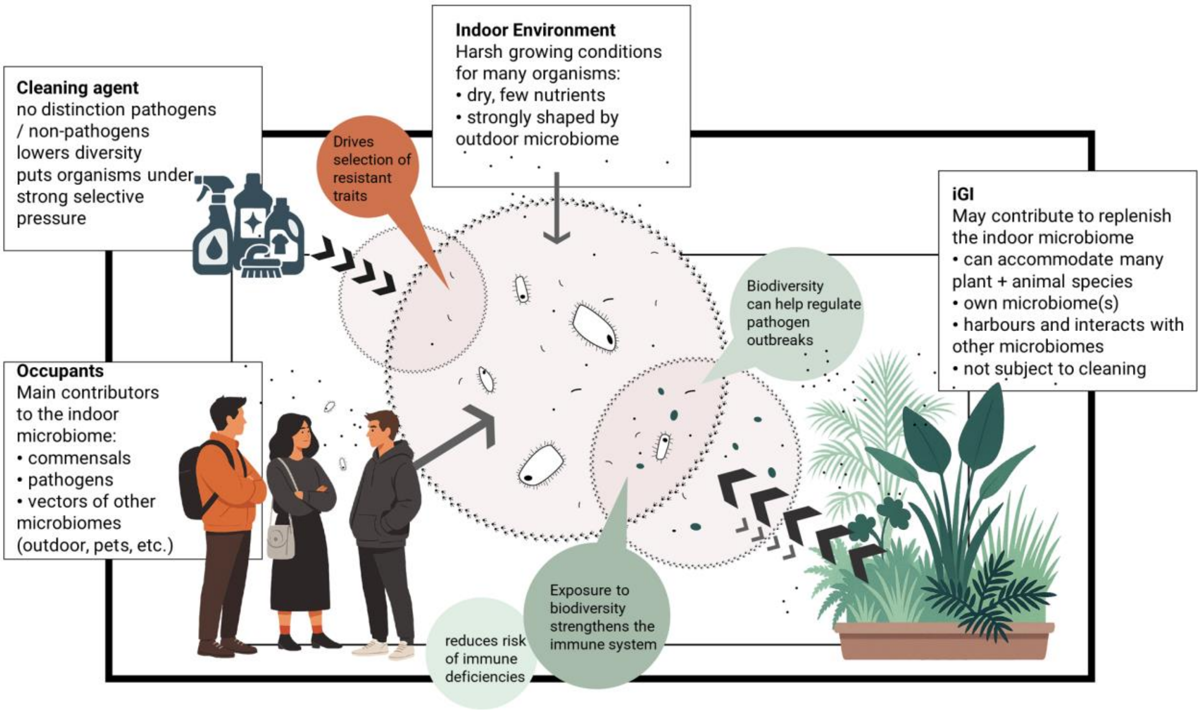


Figure 7. Conceptual representation of a symbiotic indoor environment highlighting the potential role of living indoor plants in shaping indoor microbial diversity (Source: authors' original illustration).

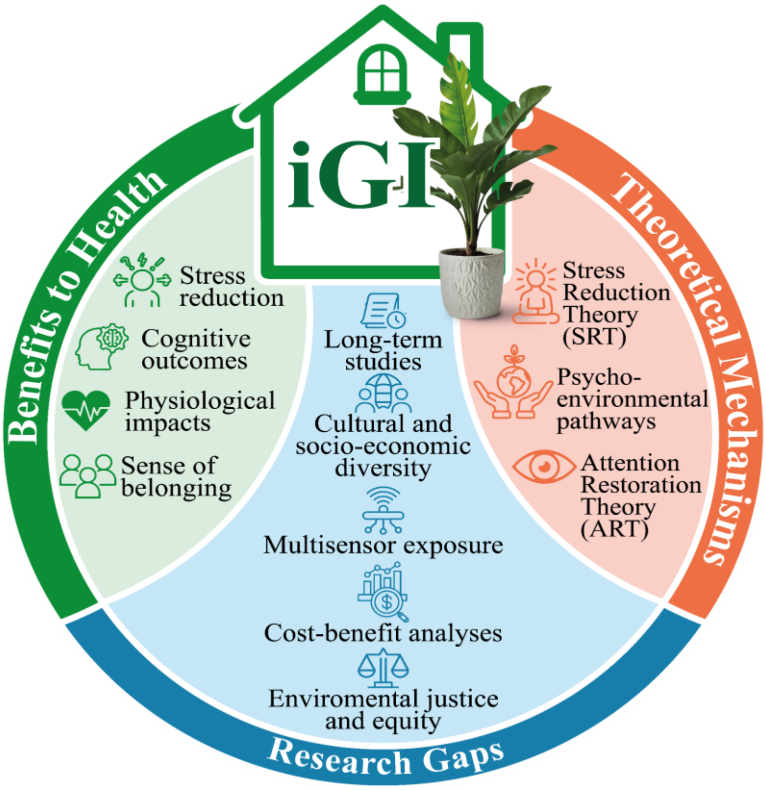


Figure 8. Evidence suggests that iGI can promote stress reduction and cognitive/physiological benefits, yet there are still key research gaps in long-term, multisensory, and equitable approaches (Source: authors' original illustration).

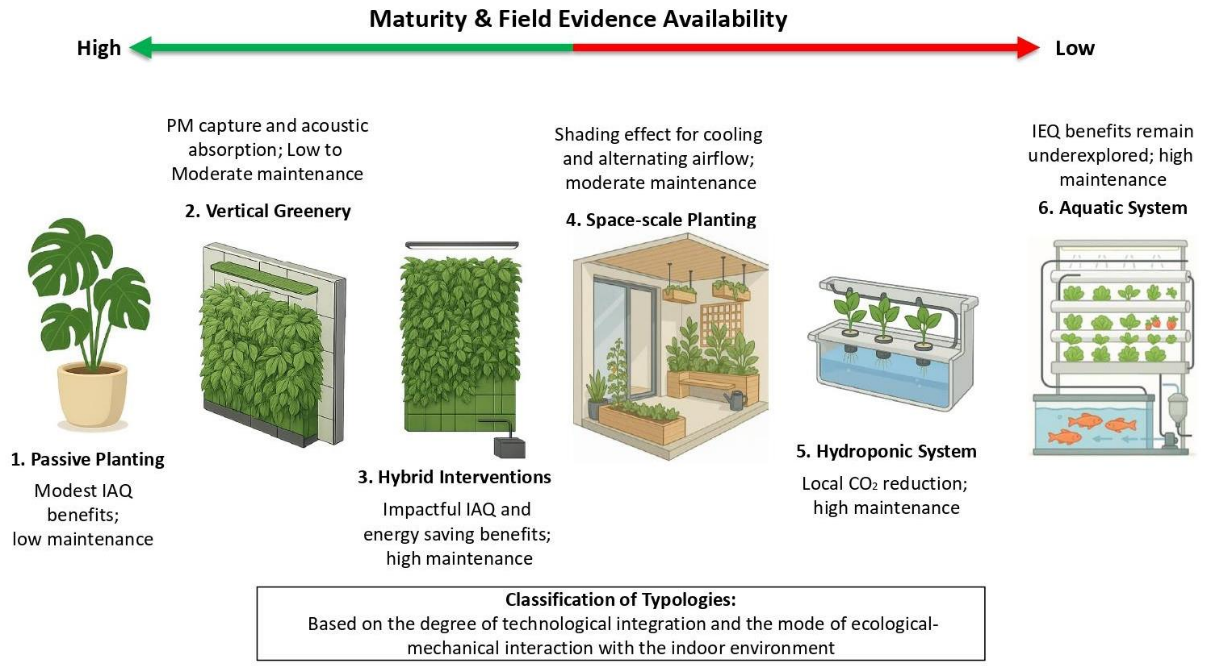


Figure 9. Data availability of iGI typologies along their associated indoor environmental quality impact and ease of maintenance (Source: authors' original illustration).

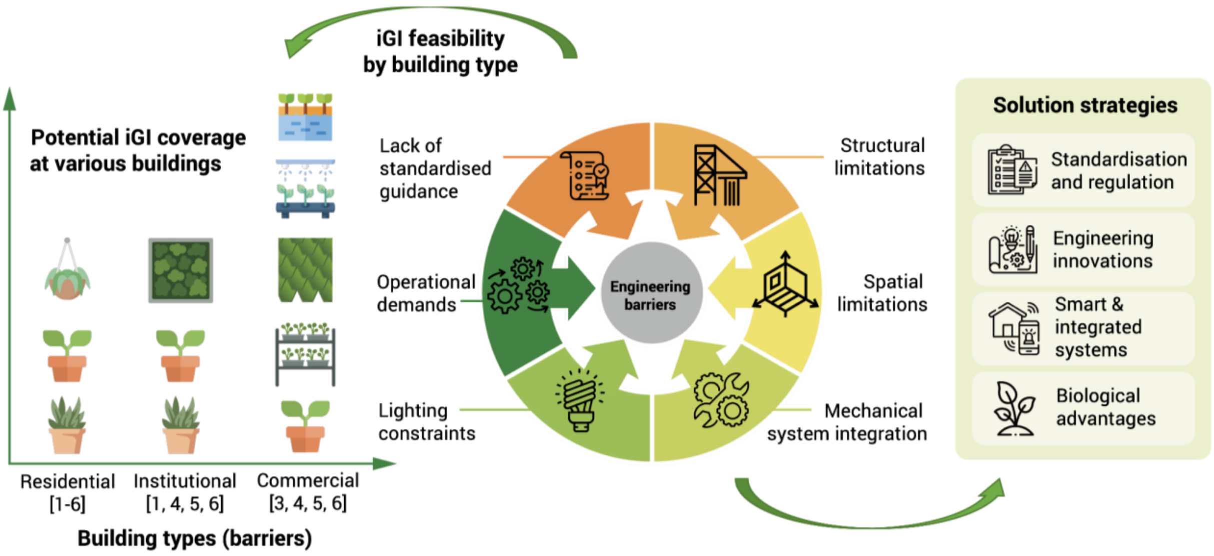
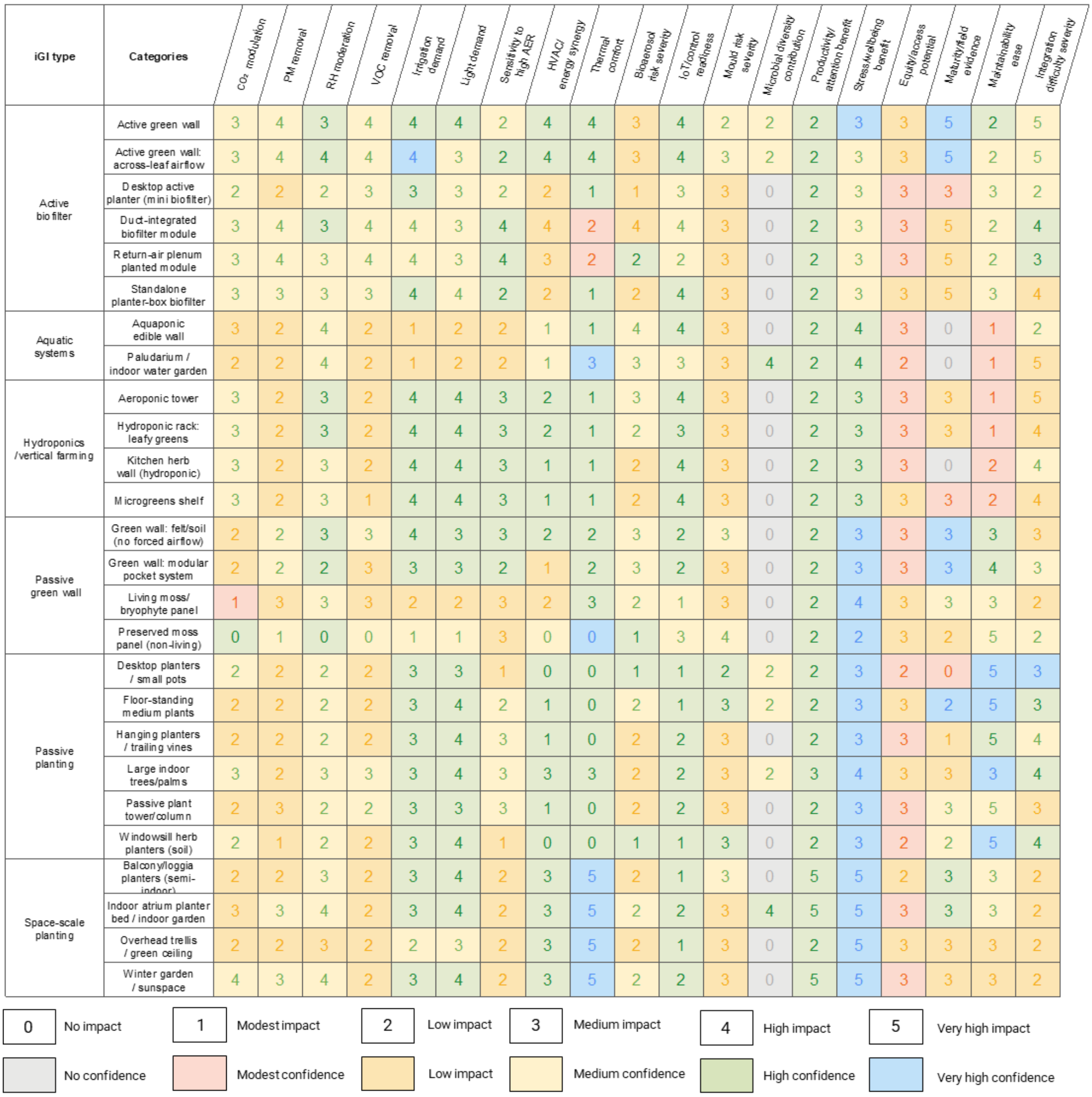


Figure 10. Engineering barriers and solution strategies for IGI. The diagram illustrates barrier categories, their impact across building types, corresponding potential iGI coverage, and pathways to overcome challenges through standardisation, engineering innovations, smart systems, and biological advances. In the left panel, the y-axis is unitless and provides a qualitative representation of the possible number of iGI installations across different building types, while the x-axis (values in brackets) denotes the corresponding engineering barriers illustrated in the central figure (Source: authors' original illustration).



iGI type	Categories	CO₂ modulation	PM removal	RH moderation	VOC removal	Irrigation demand	Light demand	Sensitivity to high AER	HVAC/ energy synergy	Thermal comfort	Bioaerosol risk severity	IoT/control readiness	Mould risk severity	Microbial diversity contribution	Productivity/ attention benefit	Stress/wellbeing benefit	Equity/access potential	Maturity/field evidence	Maintainability ease	Integration difficulty severity
Active biofilter	Active green wall	3	4	3	4	4	4	2	4	4	3	4	2	2	2	3	3	5	2	5
	Active green wall: across-leaf airflow	3	4	4	4	4	3	2	4	4	3	4	3	2	2	3	3	5	2	5
	Desktop active planter (mini biofilter)	2	2	2	3	3	3	2	2	1	1	3	3	0	2	3	3	3	3	2
	Duct-integrated biofilter module	3	4	3	4	4	3	4	4	2	4	4	3	0	2	3	3	5	2	4
	Return-air plenum planted module	3	4	3	4	4	3	4	3	2	2	2	3	0	2	3	3	5	2	3
	Standalone planter-box biofilter	3	3	3	3	4	4	2	2	1	2	4	3	0	2	3	3	5	3	4
Aquatic systems	Aquaponic edible wall	3	2	4	2	1	2	2	1	1	4	4	3	0	2	4	3	0	1	2
	Paludarium / indoor water garden	2	2	4	2	1	2	2	1	3	3	3	3	4	2	4	2	0	1	5
Hydroponics /vertical farming	Aeroponic tower	3	2	3	2	4	4	3	2	1	3	4	3	0	2	3	3	3	1	5
	Hydroponic rack: leafy greens	3	2	3	2	4	4	3	2	1	2	3	3	0	2	3	3	3	1	4
	Kitchen herb wall (hydroponic)	3	2	3	2	4	4	3	1	1	2	4	3	0	2	3	3	0	2	4
	Microgreens shelf	3	2	3	1	4	4	3	1	1	2	4	3	0	2	3	3	3	2	4
Passive green wall	Green wall: felt/soil (no forced airflow)	2	2	3	3	4	3	3	2	2	3	2	3	0	2	3	3	3	3	3
	Green wall: modular pocket system	2	2	2	3	3	3	2	1	2	3	2	3	0	2	3	3	3	4	3
	Living moss/ bryophyte panel	1	3	3	3	2	2	3	2	3	2	1	3	0	2	4	3	3	3	2
	Preserved moss panel (non-living)	0	1	0	0	1	1	3	0	0	1	3	4	0	2	2	3	2	5	2
Passive planting	Desktop planters / small pots	2	2	2	2	3	3	1	0	0	1	1	2	2	2	3	2	0	5	3
	Floor-standing medium plants	2	2	2	2	3	4	2	1	0	2	1	3	2	2	3	3	2	5	3
	Hanging planters / trailing vines	2	2	2	2	3	4	3	1	0	2	2	3	0	2	3	3	1	5	4
	Large indoor trees/palms	3	2	3	3	3	4	3	3	3	2	2	3	2	3	4	3	3	3	4
	Passive plant tower/column	2	3	2	2	3	3	3	1	0	2	2	3	0	2	3	3	3	5	3
	Windowsill herb planters (soil)	2	1	2	2	3	4	1	0	0	1	1	3	0	2	3	2	2	5	4
Space-scale planting	Balcony/loggia planters (semi-indoor)	2	2	3	2	3	4	2	3	5	2	1	3	0	5	5	2	3	3	2
	Indoor atrium planter bed / indoor garden	3	3	4	2	3	4	2	3	5	2	2	3	4	5	5	3	3	3	2
	Overhead trellis / green ceiling	2	2	3	2	2	3	2	3	5	2	1	3	0	2	5	3	3	3	2
	Winter garden / sunspace	4	3	4	2	3	4	2	3	5	2	2	3	0	5	5	3	3	3	2

0	No impact	1	Modest impact	2	Low impact	3	Medium impact	4	High impact	5	Very high impact
⬜	No confidence	🟥	Modest confidence	🟧	Low impact	🟨	Medium confidence	🟩	High confidence	🟦	Very high confidence

Figure 11. Impact of twenty-six indoor greening typologies on twenty indicators identified through Q1-10. Two ratings are provided for each box: impact score (0-5) and a confidence level via colour code (Source: authors' original illustration).